SLAC Seminar

Supersymmetry Searches with Trileptons @ CDF

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On behalf of the CDF Collaboration

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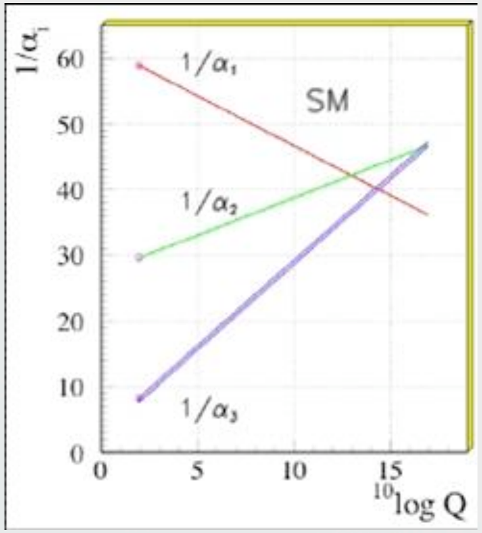
Outline

- Introduction
  - Why go beyond the Standard Model
  - Supersymmetry recap
  - The trilepton signature
- CDF: the Collider Detector at Fermilab
- The Analysis Approach
- Interpreting the results
  - The new CDF limit on the chargino mass
- Conclusions and outlook

Introduction

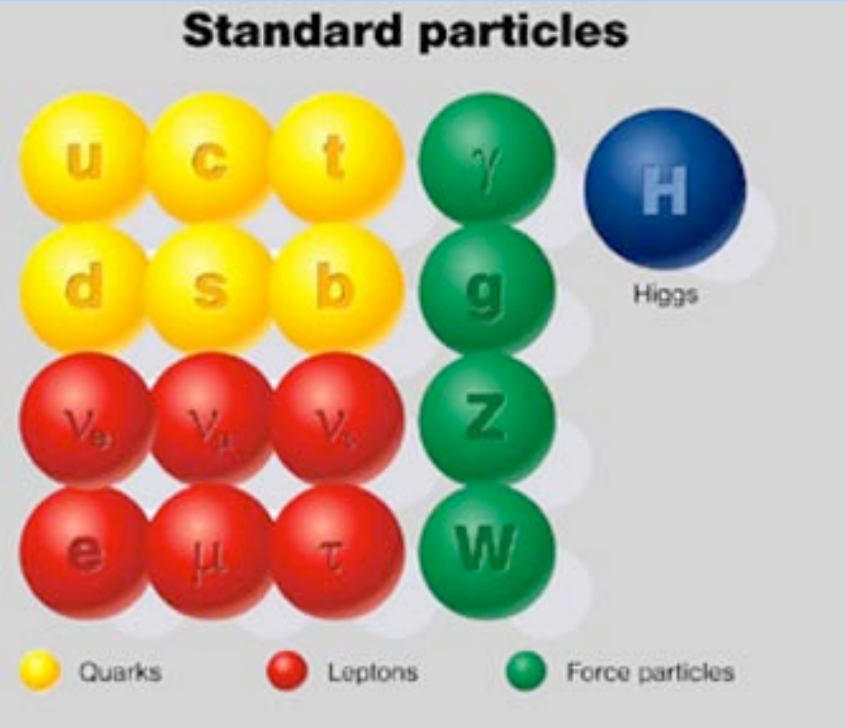
Motivation

- The Standard Model (SM) provides a successful description of presently known phenomena
- However the SM fails to address adequately some important issues
  - The Hierarchy problem
  - Electroweak symmetry breaking mechanism
  - Gauge coupling unification
  - Family structure and fermion masses
  - Cosmological challenges
    - Gravitational interactions
    - The origin of dark matter in the Universe
    - Matter-Antimatter asymmetry



Supersymmetry

- Extends the SM by adding a new spin symmetry
  - Boson ⇔ Fermion
  - SUSY more than doubles SM particle spectrum



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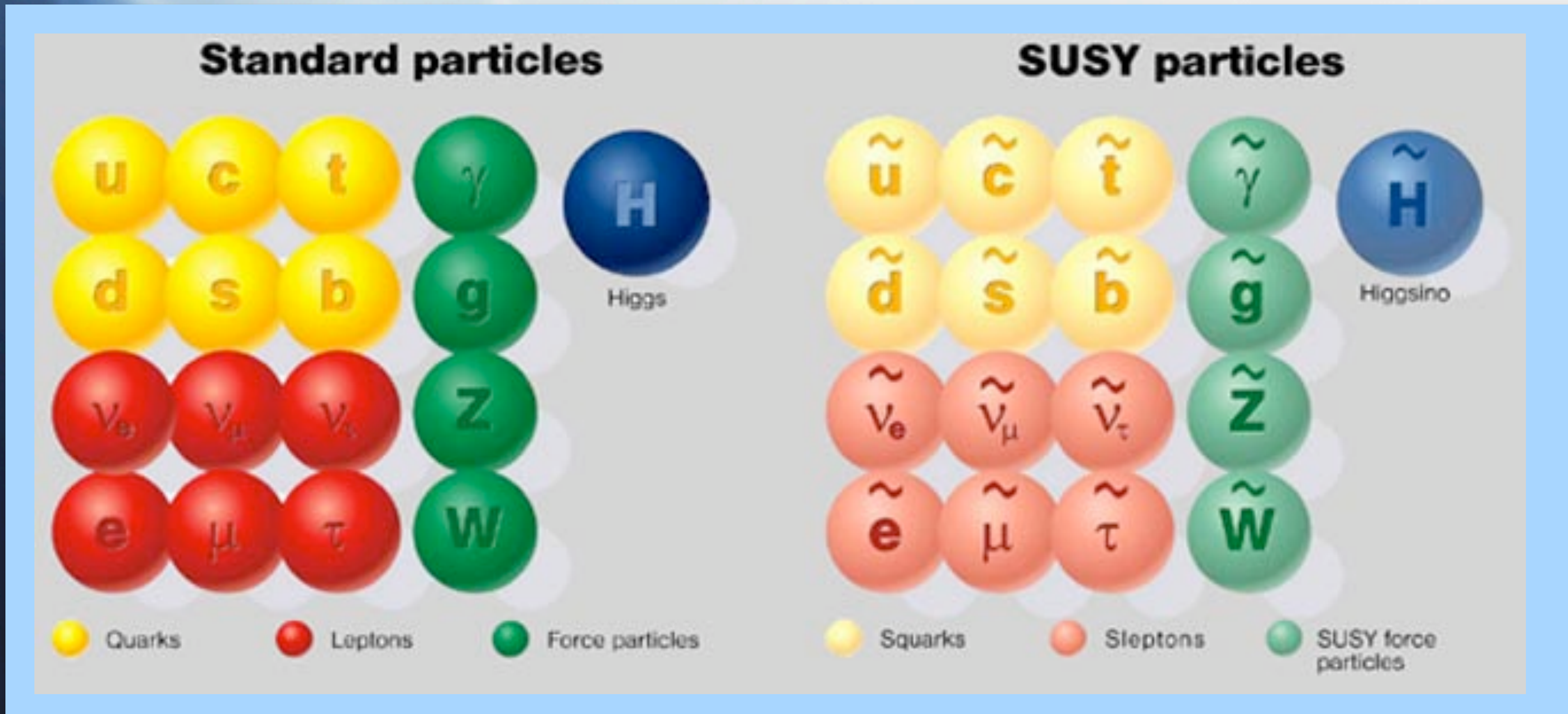
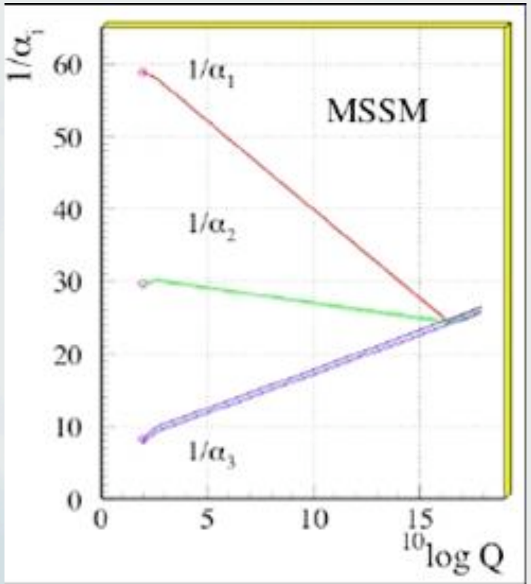


Supersymmetry

- A priori, in the superpotential, terms violating lepton and baryon number are allowed
  - Leading to rapid proton decay
- To suppress this, a common assumption is to impose a discrete symmetry called R parity
  - Additional multiplicative quantum number
  - $R_p = (-1)^{2s+3B+L}$
  - It follows that $R_p = 1$ for SM particles and $R_p = -1$ for superparticles
- Immediate consequences of R_p conservation
  - SUSY particles are pair produced
  - The Lightest Supersymmetric Particle (LSP) is stable

Advantages of Supersymmetry

- SUSY naturally solves open SM issues
  - SUSY solves the hierarchy problem
    - Quadratic divergences in the Higgs self-energy corrections become logarithmic
  - In R_p conserved scenarios, the cosmological relic of the stable LSP provides a good candidate for cold dark matter
  - SUSY provides a framework for gauge coupling unification



SUSY phenomenology

- No experimental evidence of SUSY yet
  - It follows that SUSY must be a broken symmetry
- The breaking mechanism
  - Determines phenomenology
  - Determines search strategy
  - mSUGRA is our benchmark model

mSUGRA

mSUGRA = minimal Super GRAvity

widely used benchmark model by Tevatron Run I, LHC etc.

manageable due to five parameters

- m_0: common scalar mass at GUT scale
- $m_{1/2}$: common gaugino mass at GUT scale
- tan β: ratio of Higgs vacuum expectation values
- A_0: trilinear coupling
- Sign(μ): sign of Higgs mass term

Signal Benchmark Point

m_0=60 GeV, $m_{½}$=190 GeV, tan(β)=3, A_0=0, μ>0

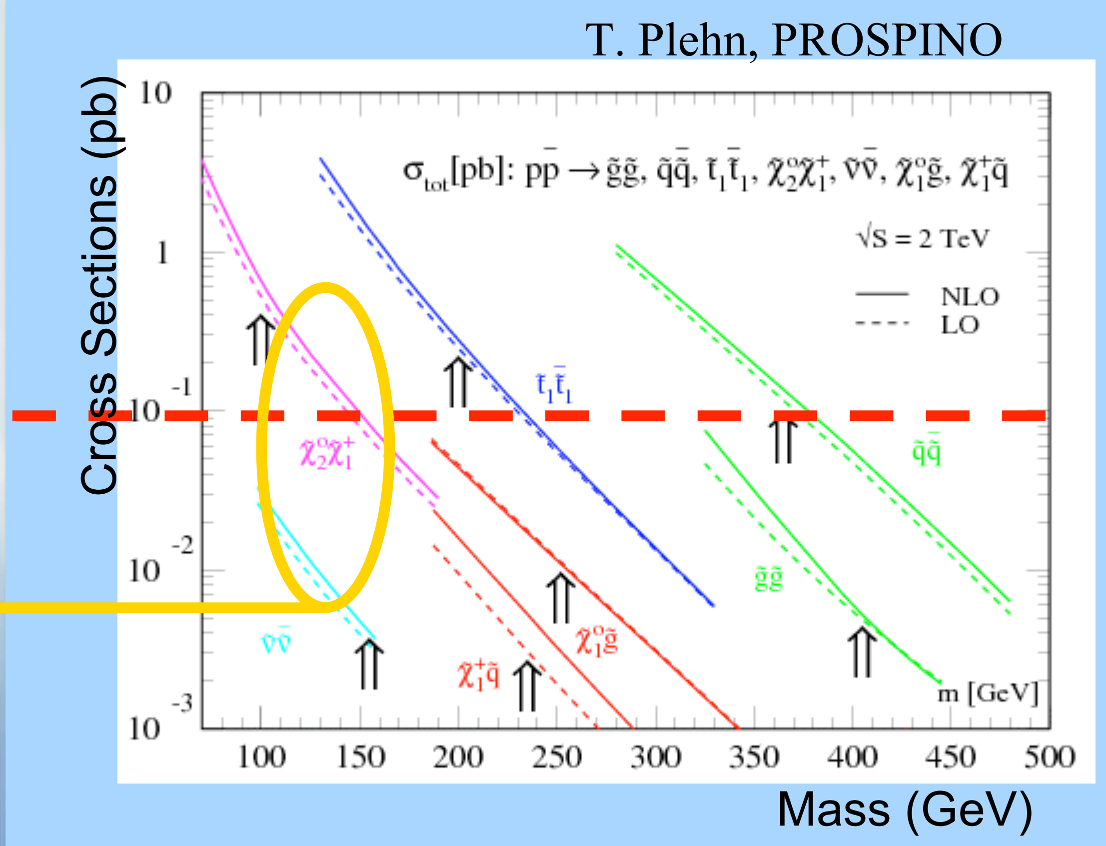
SUSY cross sections

- Most SUSY searches at hadron colliders are for:
  - Chargino-Neutralino
  - Squarks
  - Gluinos

100 events per fb-1

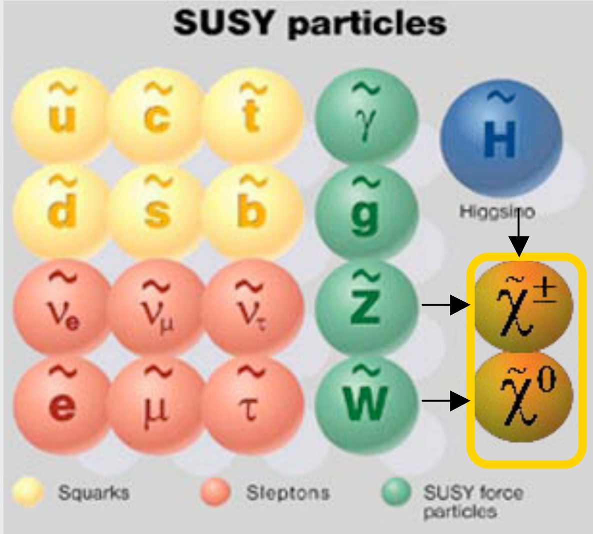
Concentrating on Chargino and Neutralino

σ(SUSY) ~ pb while
σ(pp̄) ~ 50 x 10⁹ pb



Charginos & Neutralinos

- Charginos ($\tilde{\chi}^{\pm}$) and Neutralinos ($\tilde{\chi}^{0}$) are the eigenstates of the mass matrix of the SUSY partners of the Gauge and Higgs bosons
- $\tilde{\chi}^{\pm}$ and $\tilde{\chi}^{0}$ are analogues of W and Z in SUSY
- There are four $\tilde{\chi}^{0}_{1,2,3,4}$ two $\tilde{\chi}^{\pm}_{1,2}$



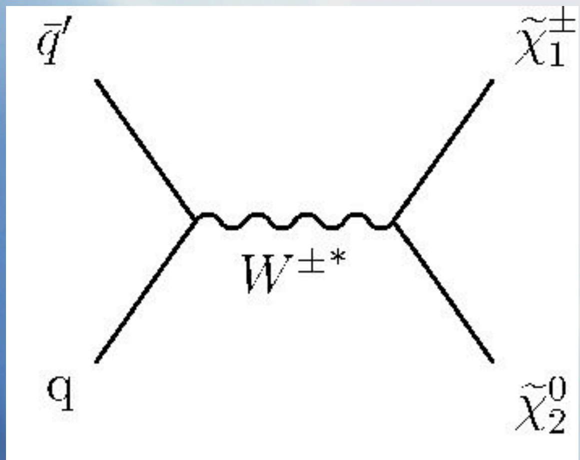
Mass ($\tilde{\chi}^{0}_{1}$) = 67 GeV
Mass ($\tilde{\chi}^{0}_{2}$) = 122 GeV
Mass ($\tilde{\chi}^{\pm}_{1}$) = 120 GeV

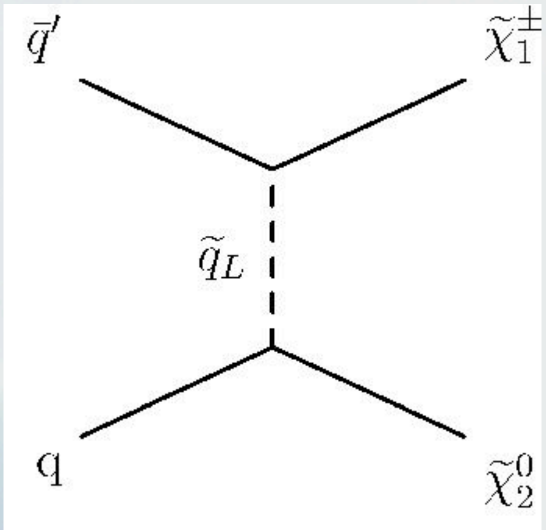
@

Signal Benchmark Point
m_0=60 GeV, $m_{1/2}$=190 GeV,
tan(β)=3, A_0=0, μ>0

Chargino & Neutralino Production

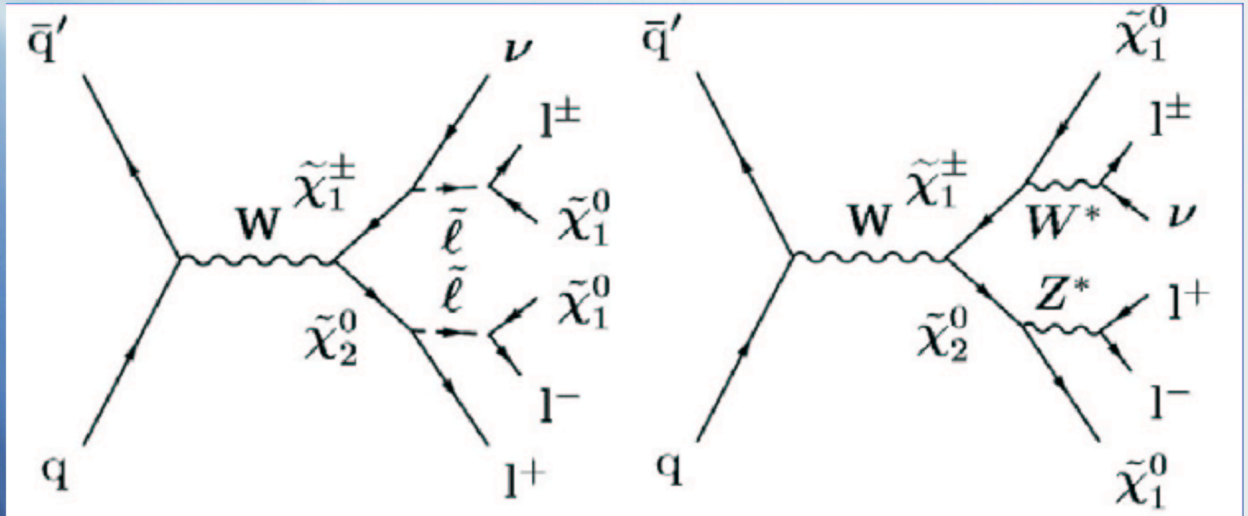
- Assuming R_p conservation
  - sparticles are pair produced
  - $\tilde{\chi}^0_1$ the LSP is stable and escapes detection
- Chargino $\tilde{\chi}^{\pm}_1$ and Neutralino $\tilde{\chi}^0_2$ can be produced in association





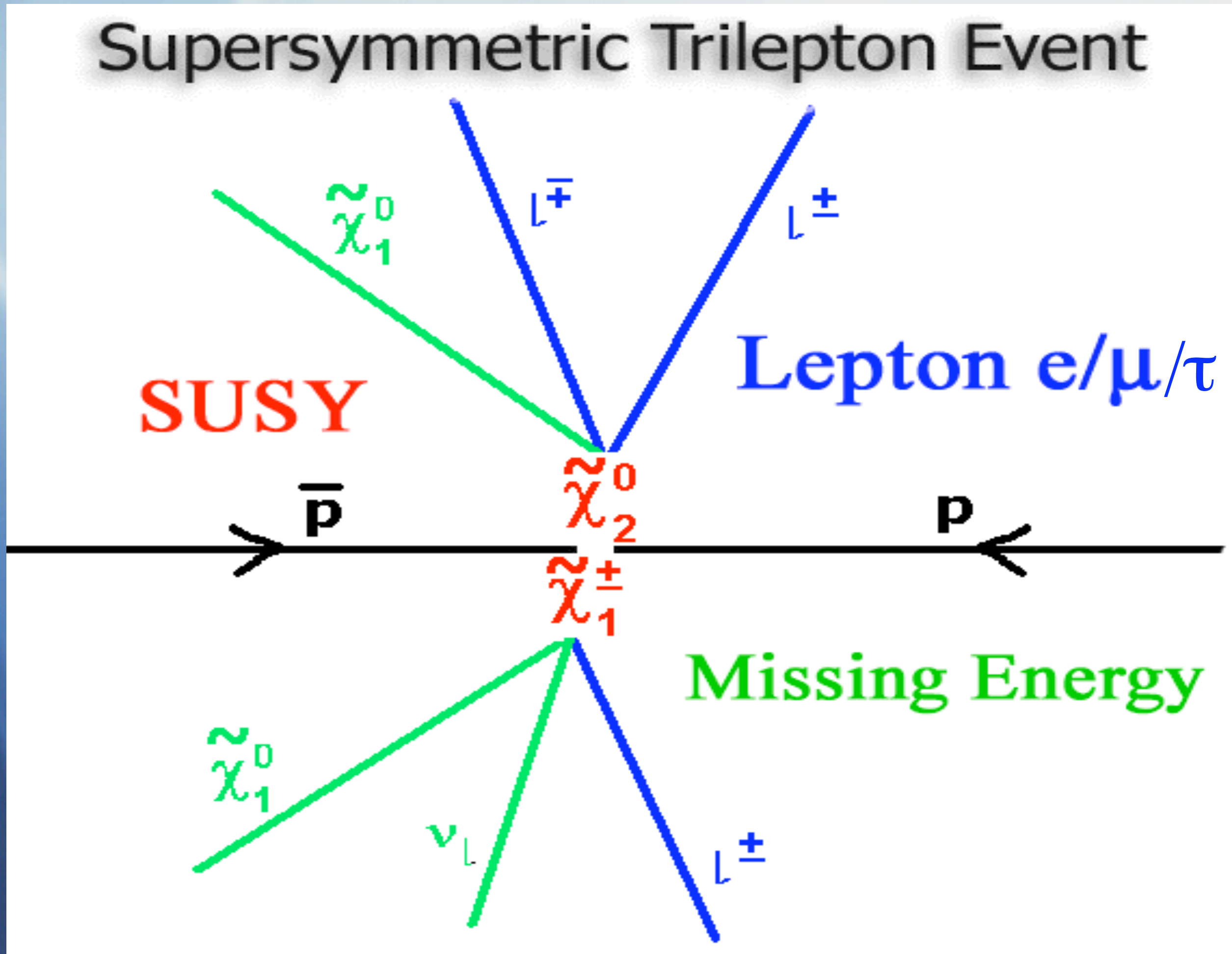
Chargino & Neutralino Decay

Chargino and Neutralino can decay via virtual W, Z or sleptons leading to a final state with 3 charged leptons, 2 LSPs and 1 neutrino.



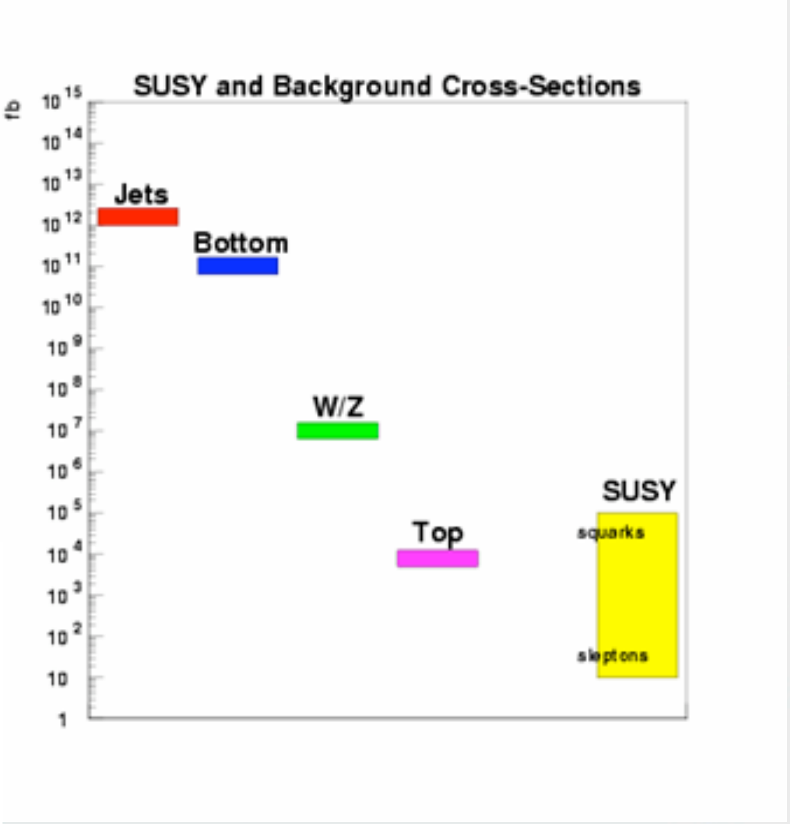
+interfering t-channel squark exchange diagrams

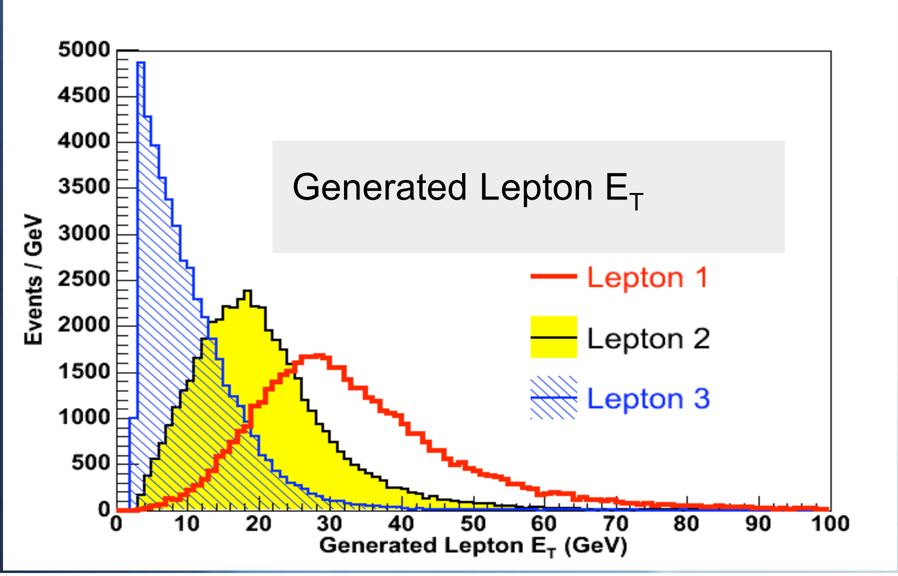
Signature of Interest



Multilepton Final States

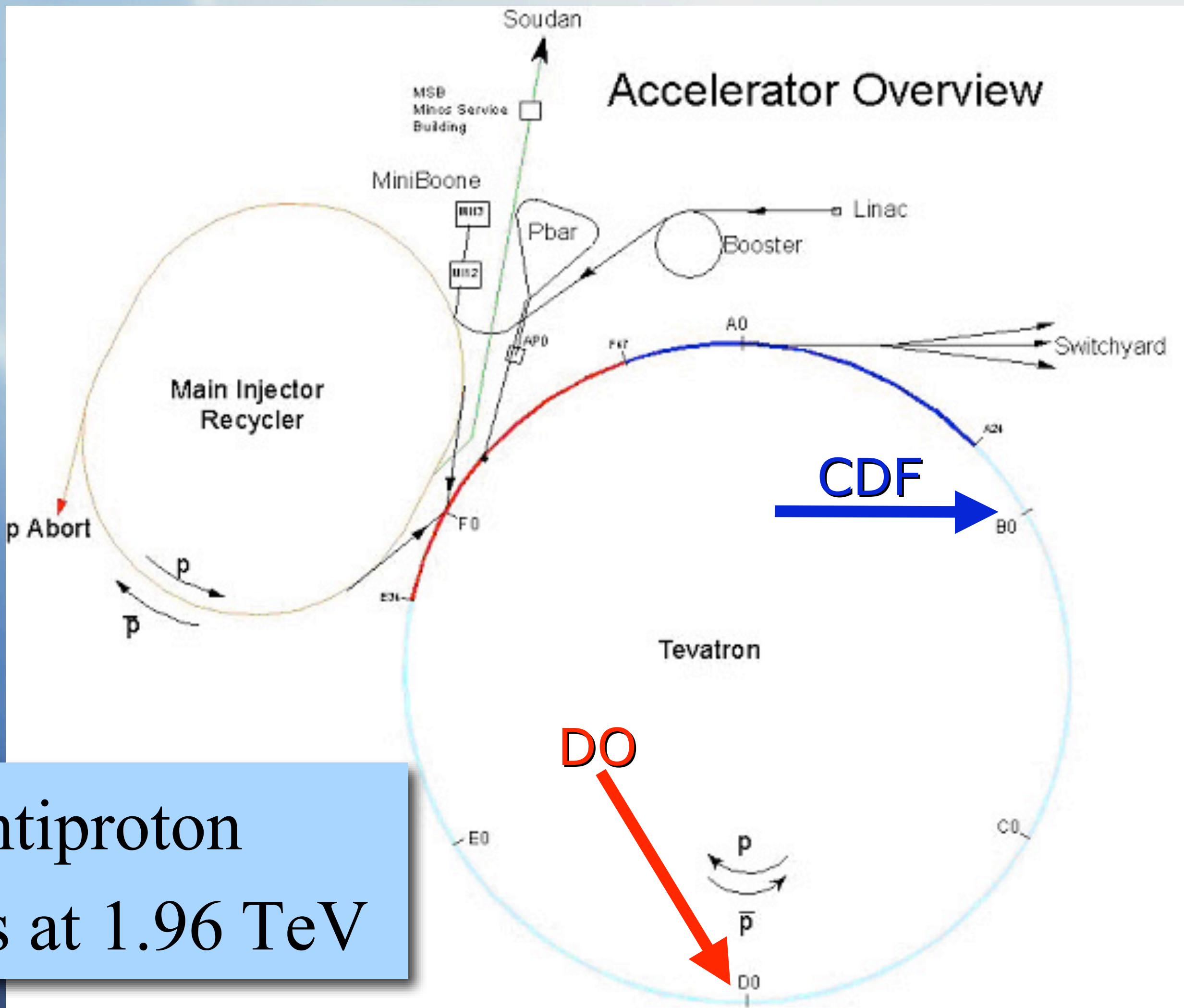
- Appealing for other SUSY searches
  - RPV SUSY processes
- Very clean
  - Particularly powerful @ hadron colliders where QCD background dominates
- But leptons from chain decays
  - Relatively low p_T (< 20 GeV/c)





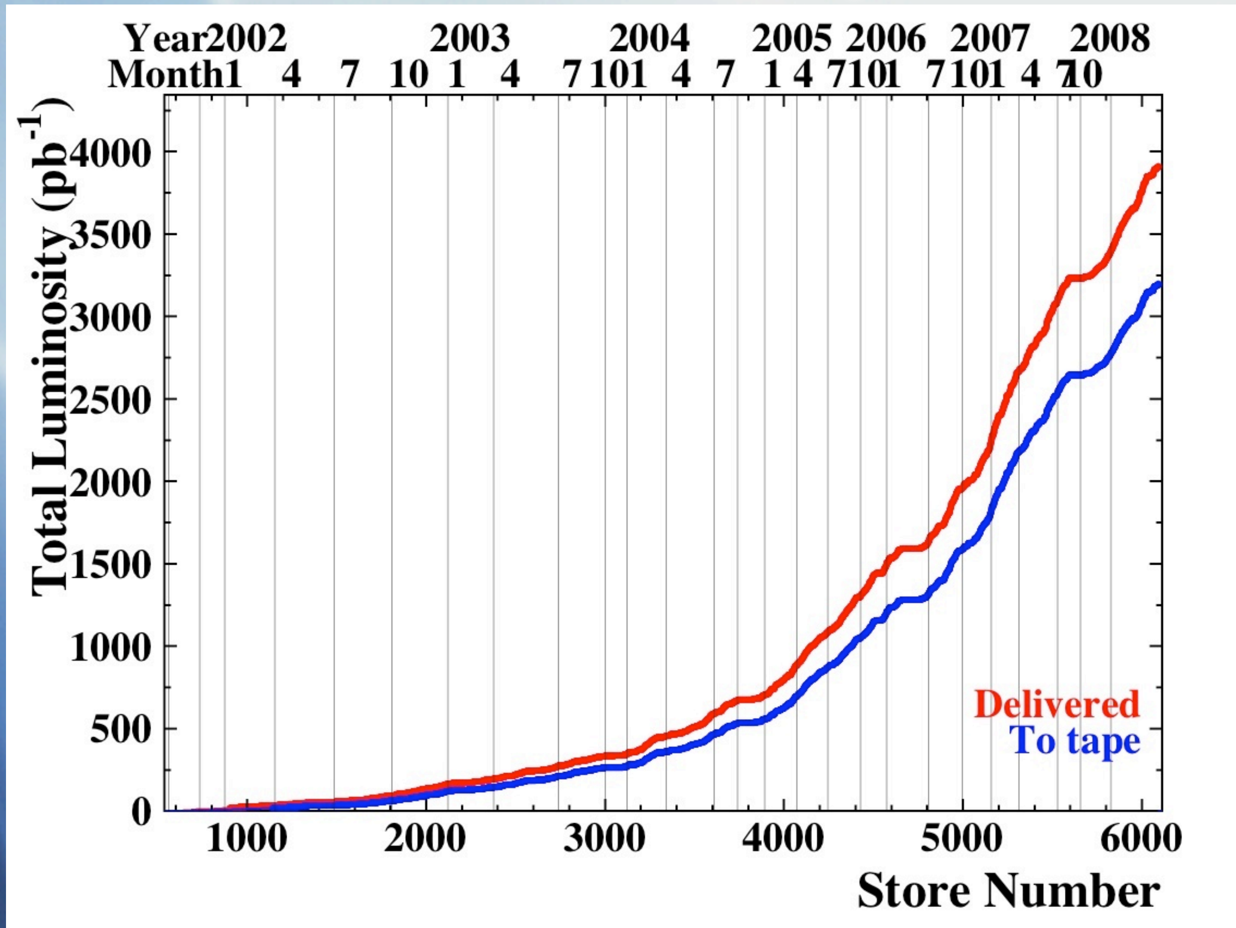
CDF
the Collider Detector at Fermilab

The Tevatron Accelerator Complex



proton-antiproton
collisions at 1.96 TeV

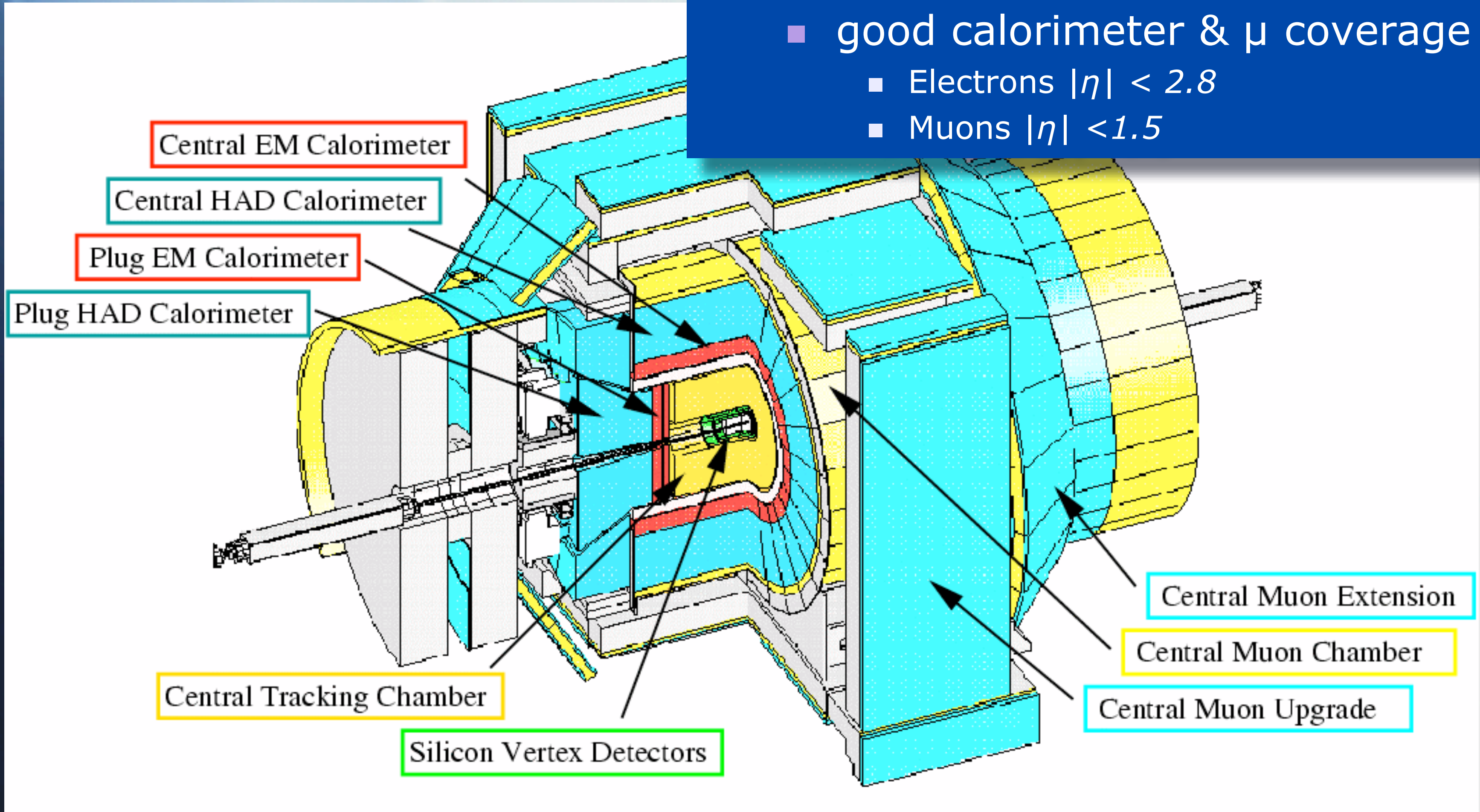
Luminosity



Total Integrated Luminosity for this result is 2.0 fb^{-1}

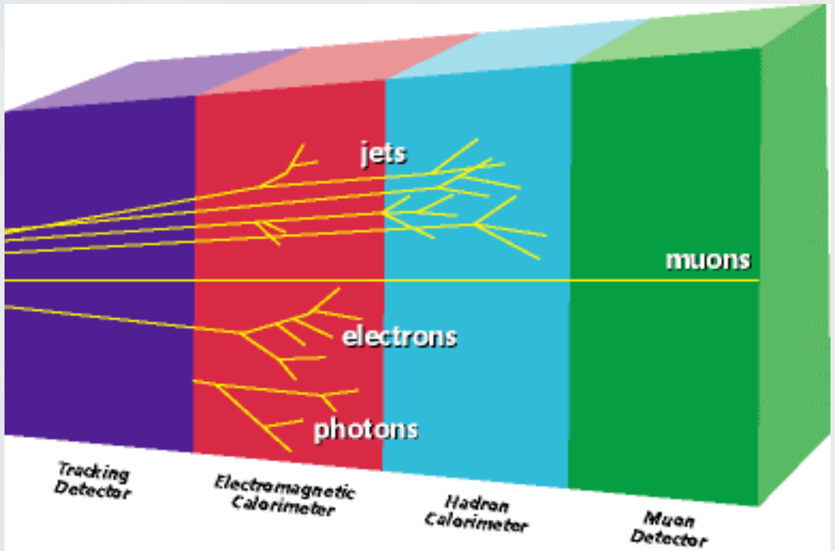
The CDF Run II Detector

- **Multipurpose Detector**
  - precision tracking
  - good calorimeter & μ coverage
    - Electrons $|\eta| < 2.8$
    - Muons $|\eta| < 1.5$



Signature Ingredients: LEPTONS

- Electrons
  - Track + EM shower
- Muons
  - Track
    + no shower in calorimeter
    + signal in muon systems
- Taus
  - Decay to electrons or muons BR=35%
  - Decay hadronically single-prong (1 charged particle) BR = 50%
    → use an isolated track to identify single-prong decay
  - Not considered the decay hadronically three-prong (3 charged particle) BR=15%



But isolated tracks also can recover electrons or muons which do not pass the standard identification

Signature Ingredients: LEPTONS

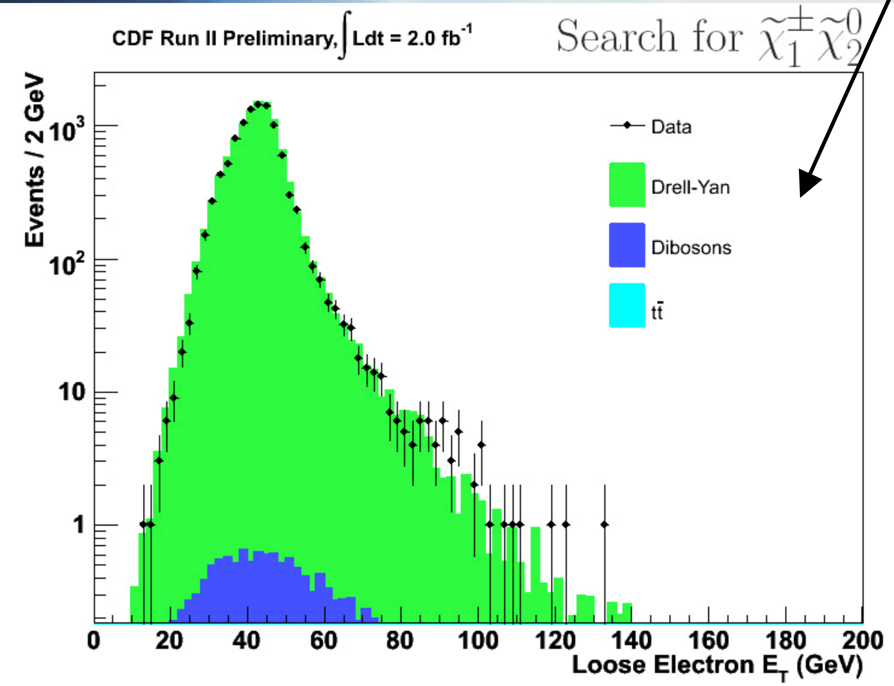
- Leptons selection

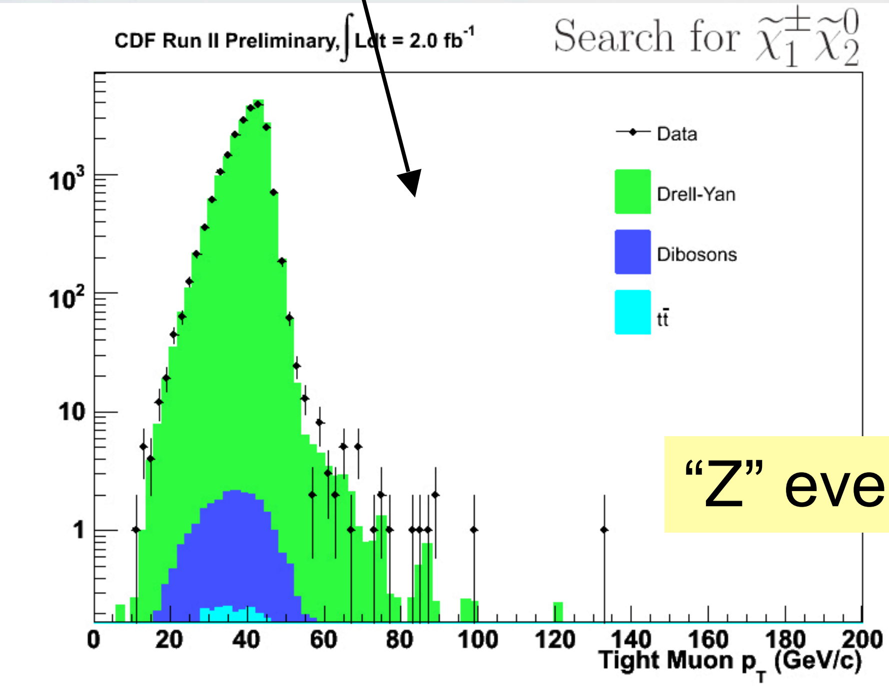
	Electrons	Muons	Taus
Tight Cuts	✓	✓	
Loose Cuts	✓	✓	
Isolated tracks	✓	✓	✓

where tight selection has some additional requirements (like the shower shape of electron in the EM calorimeter) with respect to loose selection

Signature Ingredients: LEPTONS

	Electrons	Muons	Taus
Tight Cuts	✔	✔	
Loose Cuts	✔	✔	
Isolated tracks	✔	✔	✔

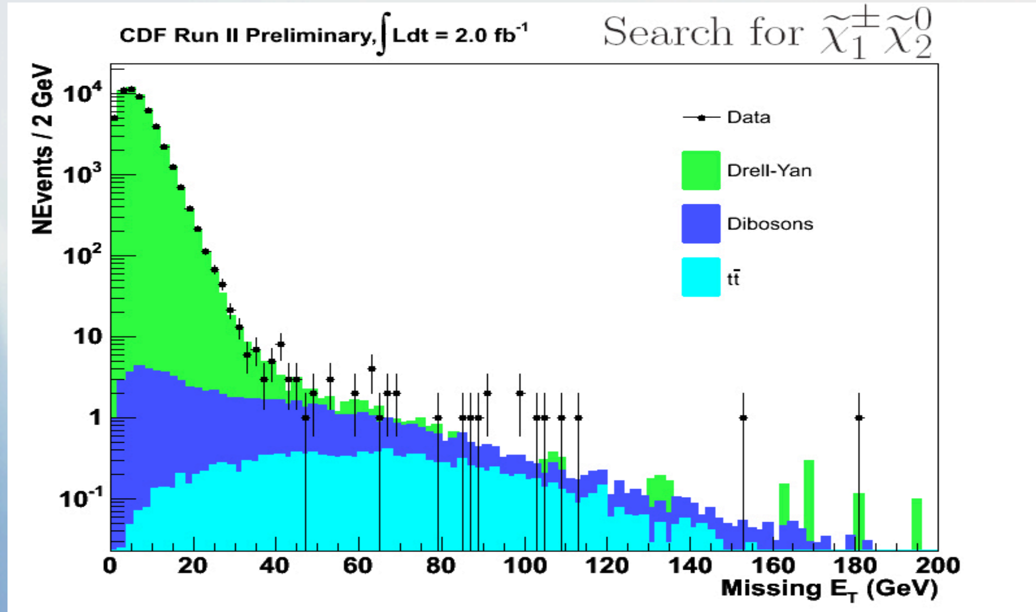




“Z” events

Signature Ingredients: MET

- 2 LSPs and 1 neutrino escape detection and contribute to the Missing Transverse Energy $\text{MET} = \Sigma E_T(\nu,\text{LSPs})$
- MET is indirectly measured in the calorimeter but needs to be corrected
  - for jet energy scale
  - for muons



Standard Model Backgrounds

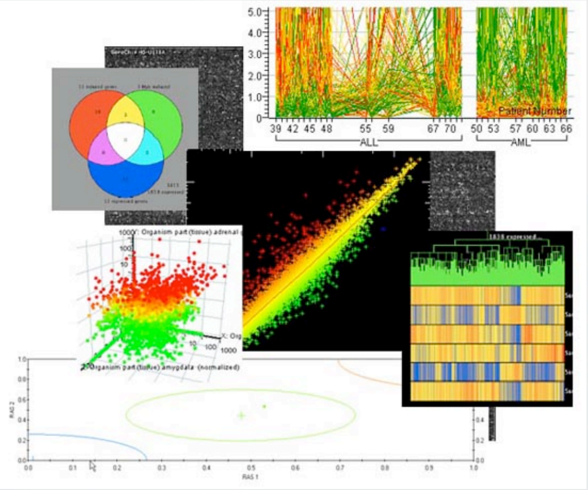
WZ	3 real leptons + MET	3 real leptons
ZZ	4 real leptons	
$t\bar{t}$	2 real leptons + MET	2 real leptons
Drell Yan (DY)	2 real leptons	
WW	2 real leptons + MET	
W+jets	1 real lepton + MET	1 real lepton

In the case of 2 or 1 real leptons there can be 1 or 2 additional lepton objects from γ conversion or a misidentified lepton (i.e. hadron misidentified as lepton or track)

Background estimation

- Estimation from Monte Carlo (MC) simulations
  - WZ, ZZ, $t\bar{t}$, DY+γ
  - All MC predictions need to be corrected for real lepton identification efficiencies and trigger efficiencies
- Rate for objects faking a lepton from DATA
  - DY + (had$\rightarrow$lep)
  - WW + (had$\rightarrow$lep)
  - W+jets + (had$\rightarrow$lep)
- Rate for Candidate Tracks from MC
  - DY + track
  - WW+ track

The Analysis Approach



The Analysis

STATISTICALLY UNBIASED ANALYSIS
performed as a COUNTING EXPERIMENT

The "signal" region is investigated in data only at the very end of the analysis

Optimization of analysis cuts
looking at MC only

Verification that backgrounds are reproduced by MC in "control regions"

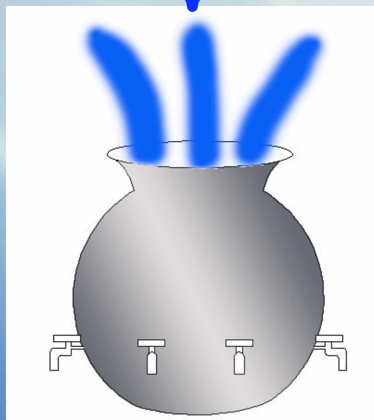
Kinematic regions where new physics expected to be small

LOOK at DATA in the SIGNAL REGION

compare number of predicted and observed events

Setting up the analysis

Overlapping data sets
collected with many different triggers



Channels chosen
on the basis of lepton content:
Mutually exclusive
Ordered in terms of purity (S/B)

S/B

3 tight leptons

2 tight & 1 loose leptons

1 tight & 2 loose leptons

2 tight lepton & 1 track

1 tight & 1 loose leptons & 1 track

Setting up the analysis

3 tight leptons	P_T (E_T) > 15, 5, 5 GeV
2 tight & 1 loose leptons	P_T (E_T) > 15, 5, 10 GeV
1 tight & 2 loose leptons	P_T (E_T) > 20, 8, 5(10 if loose muon) GeV
2 tight lepton & 1 track	P_T (E_T) > 15, 5, 5 GeV
1 tight & 1 loose lepons & 1 track	P_T (E_T) > 20, 8 (10 if loose muon), 5 GeV

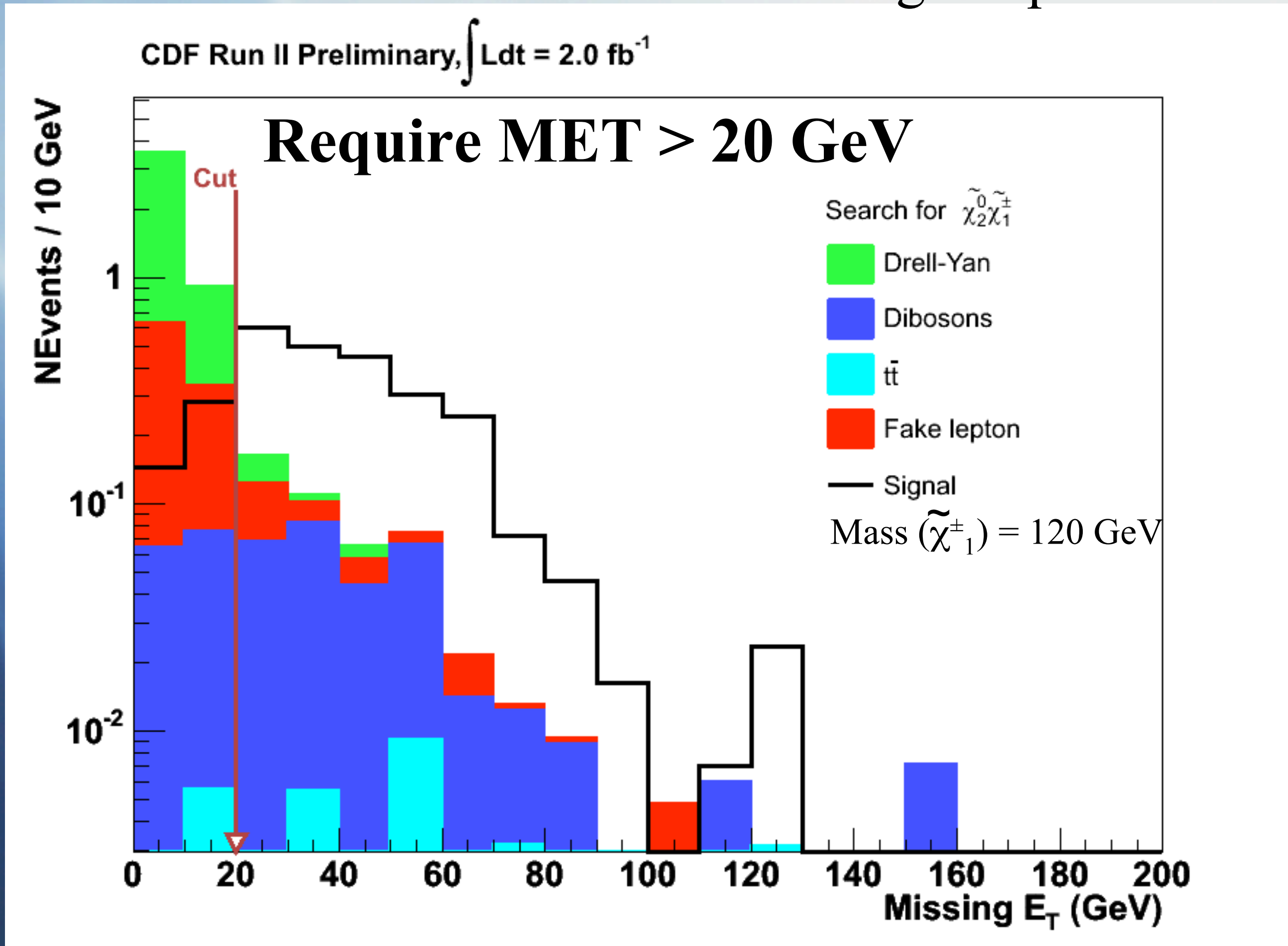
Optimization of analysis cuts

Background Reduction

WZ ZZ	On-shell contribution of Z removed by invariant mass cut for Z Off-shell contribution for ZZ reduced by MET cut Off-shell contribution from WZ hard to remove without eating on the signal
$t\bar{t}$ Had→lep	High hadronic activity reduced by cutting on Njets
DY+γ DY+track	Events with low MET reduced by requiring a lower limit on MET

Reducing Backgrounds: Drell-Yan, ZZ

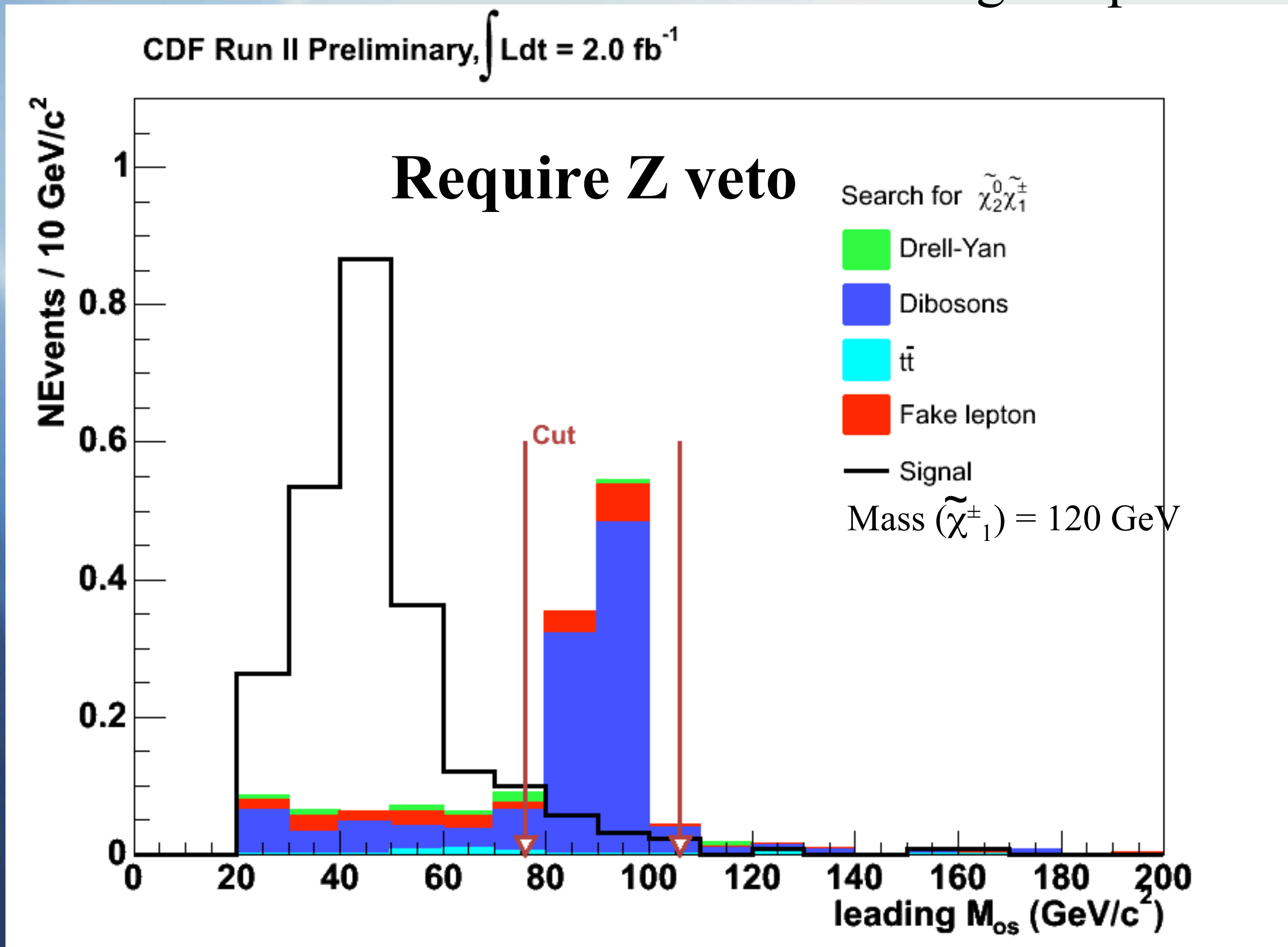
3 tight leptons



After all other selections are made

Reducing Backgrounds: WZ, ZZ on shell

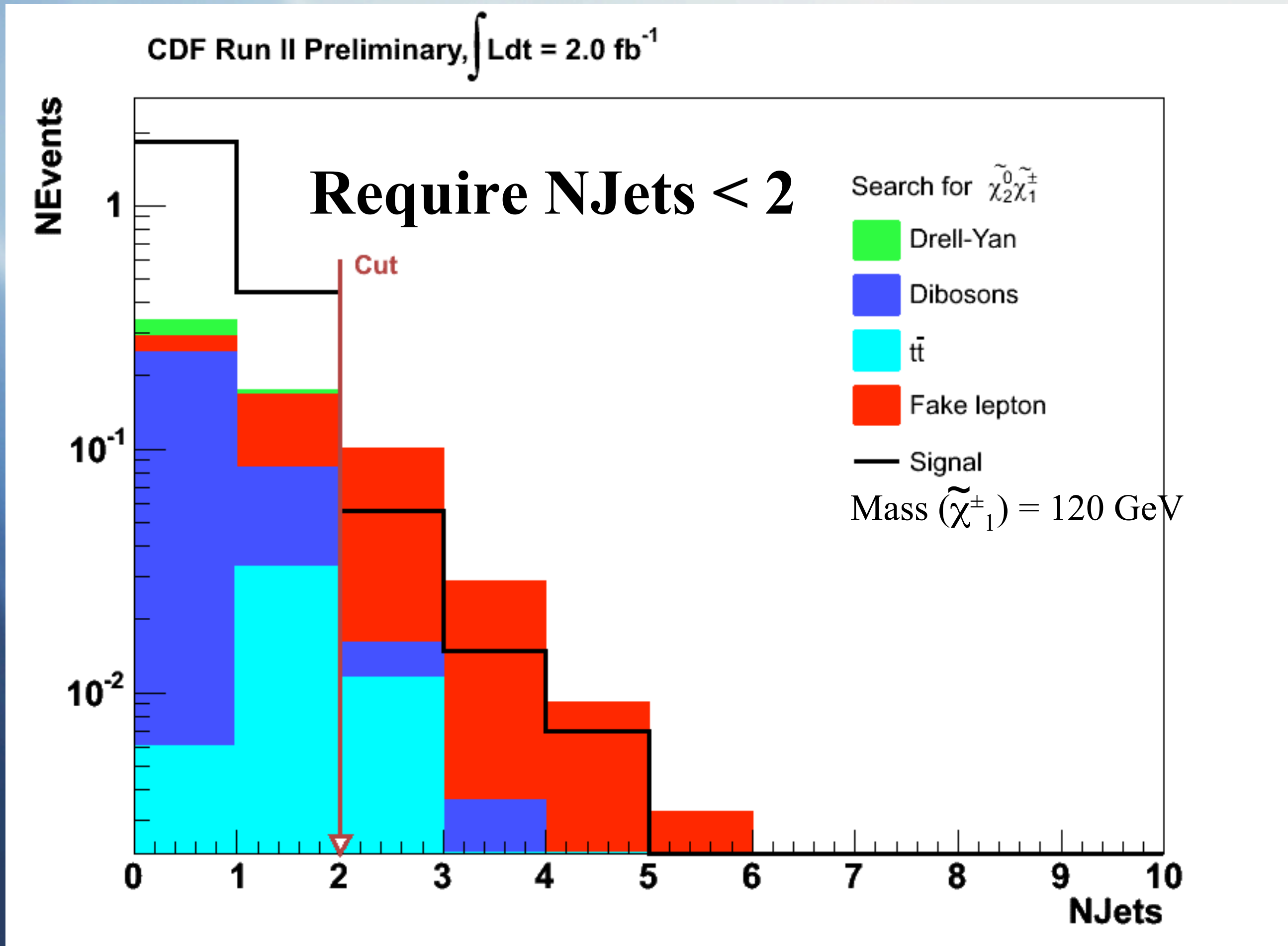
3 tight leptons



After all other selections are made

Reducing Backgrounds: top-pair, fakes

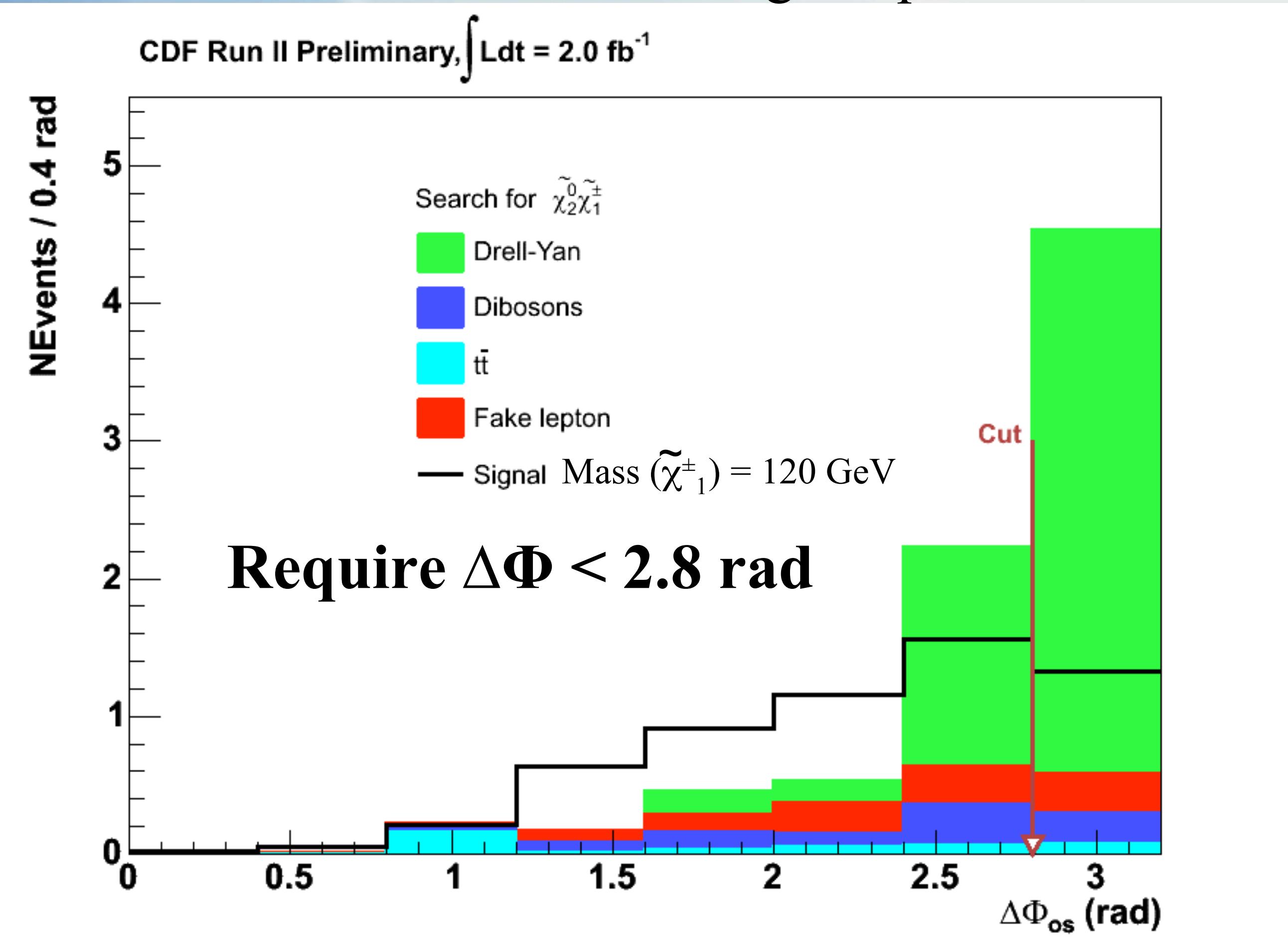
3 tight leptons



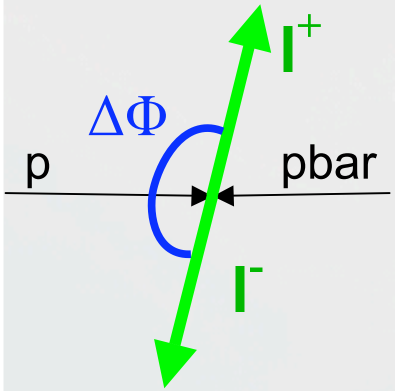
After all other selections are made

Reducing Backgrounds: Residual DY

2 tight leptons + 1 Track

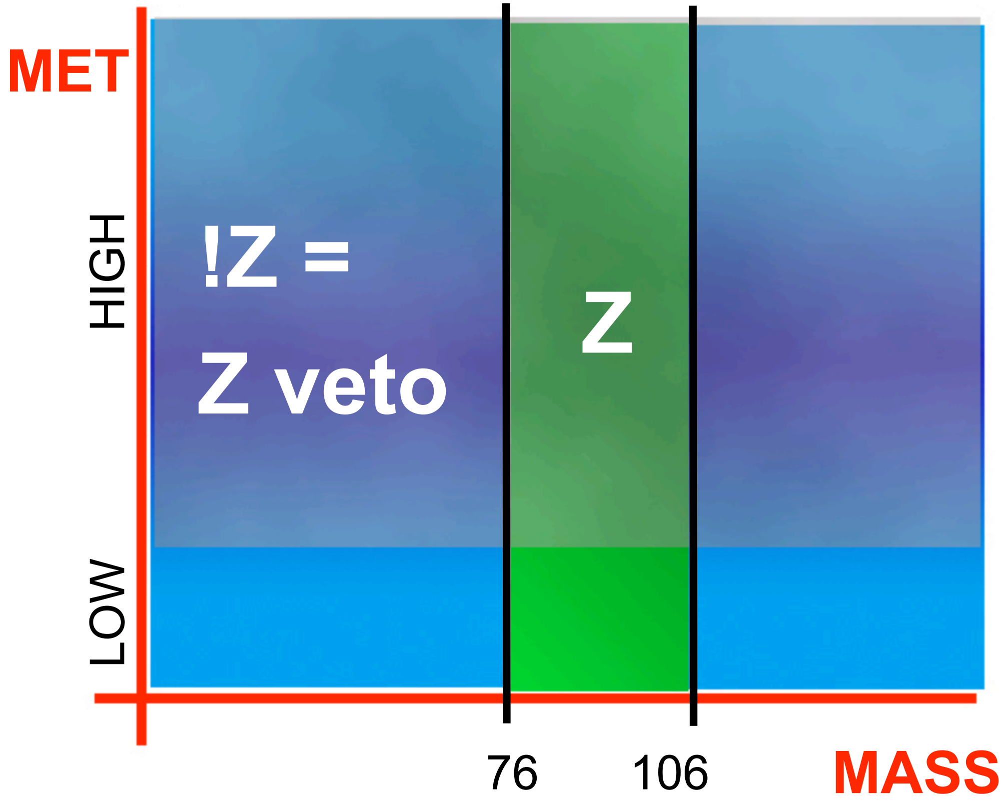


After all other selections are made



Verify the Standard Model backgrounds in "control regions"

Control Regions



START with DILEPTON EVENTS
$\rightarrow$ high statistics samples

Use Z events ($76 < M_{ll} < 106$ GeV/c^2) to test luminosity

- ✓ High P_T leptons

Use Z-veto to test low mass DY

- ✓ Low P_T leptons

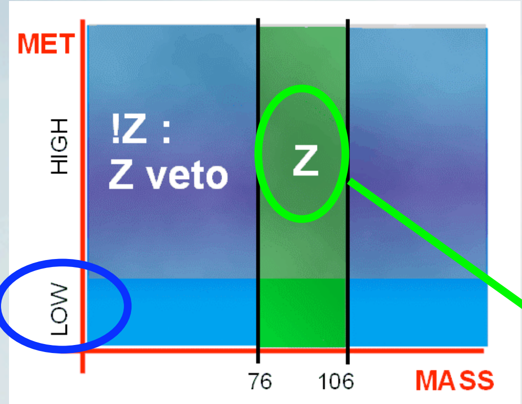
Watch kinematic distributions checking

- ✓ shapes and
- ✓ number of events

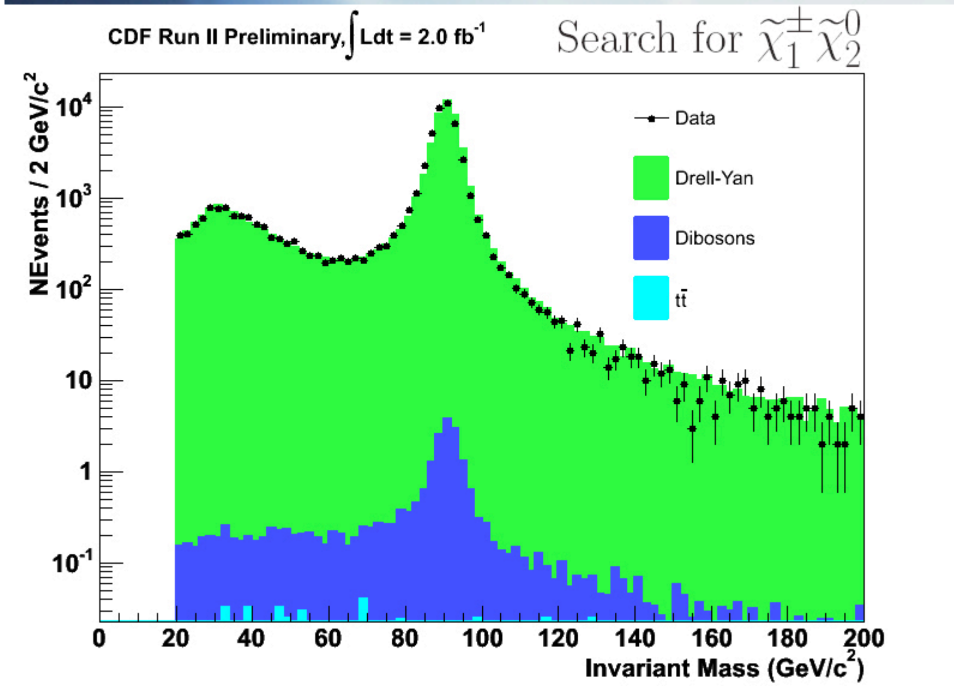
Further agreement tests:

- ✓ watch MET distributions to test corrections
- ✓ split by lepton content (ee,μμ,eμ)

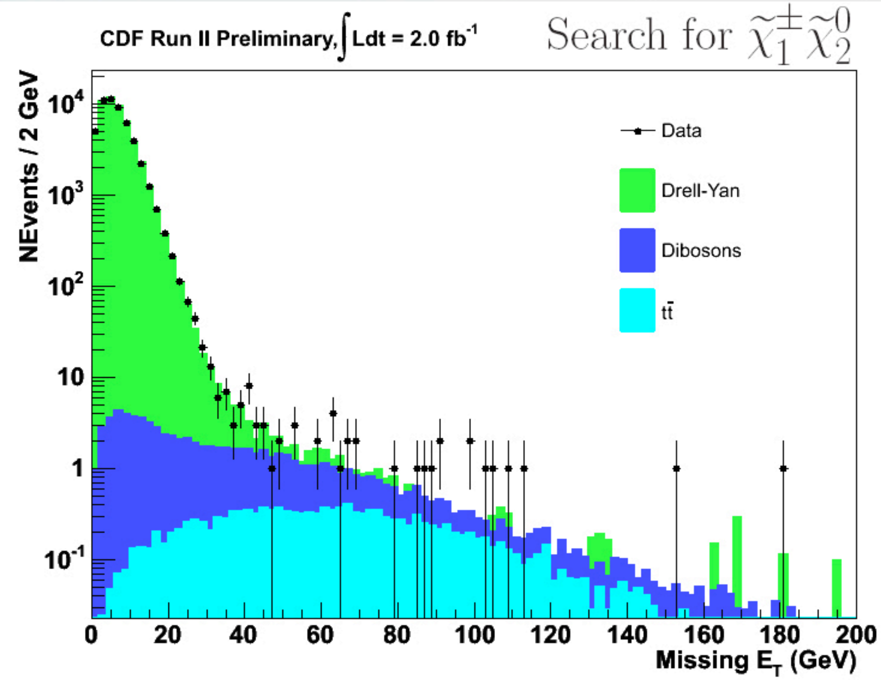
Control Regions : Dileptons



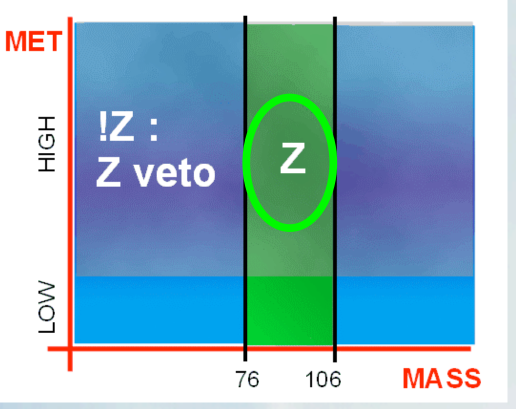
Dilepton Invariant Mass



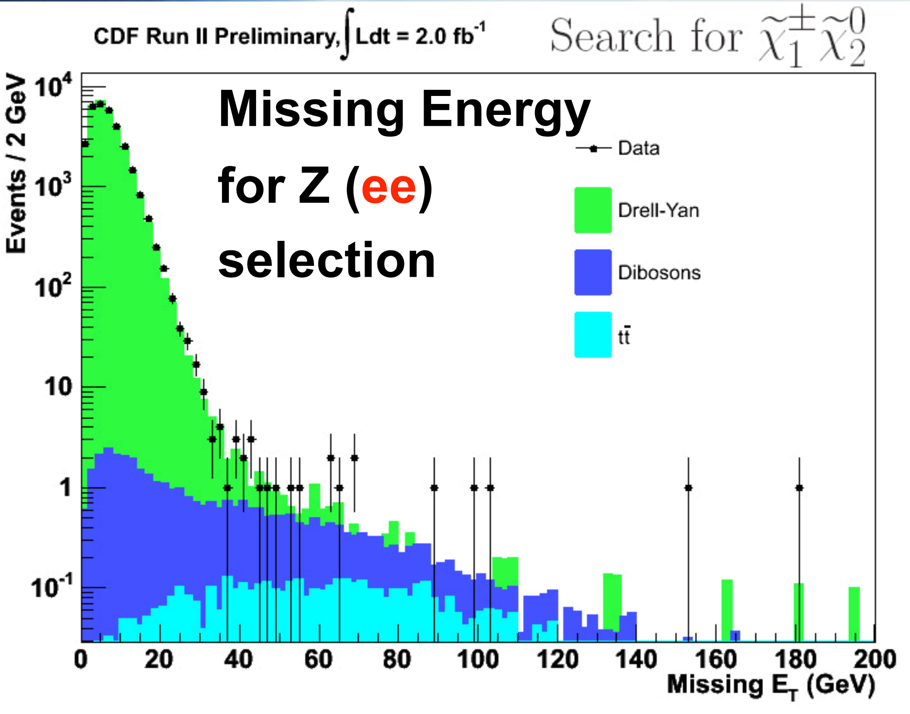
Missing Energy for Z selection

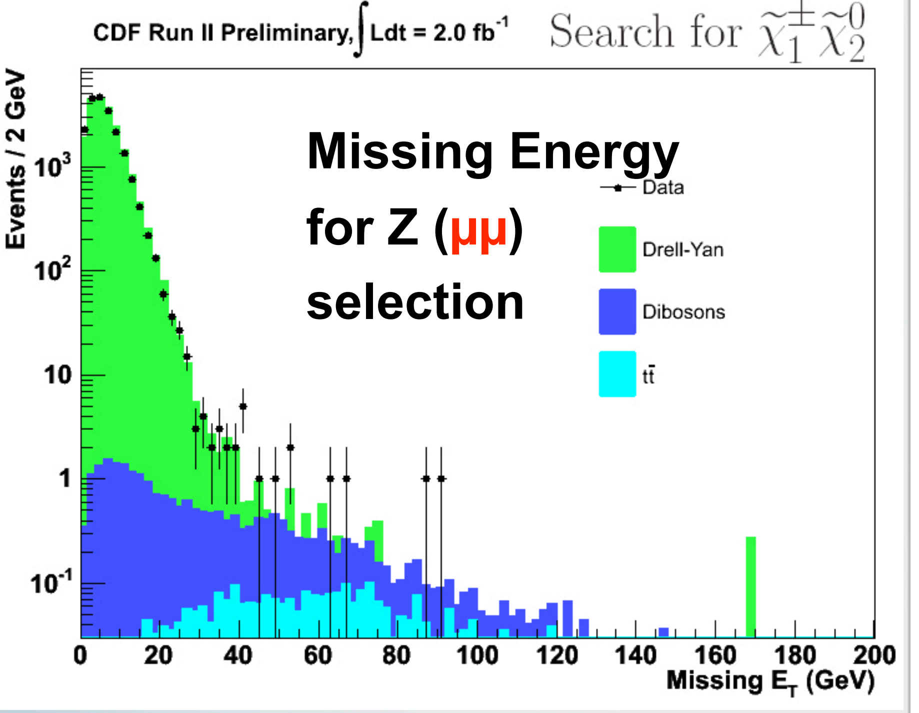


Control Regions : Dileptons

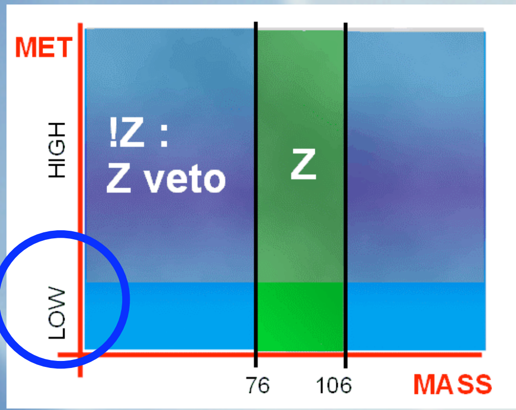


Breaking Missing Energy into **Z→ee** and **Z→μμ**

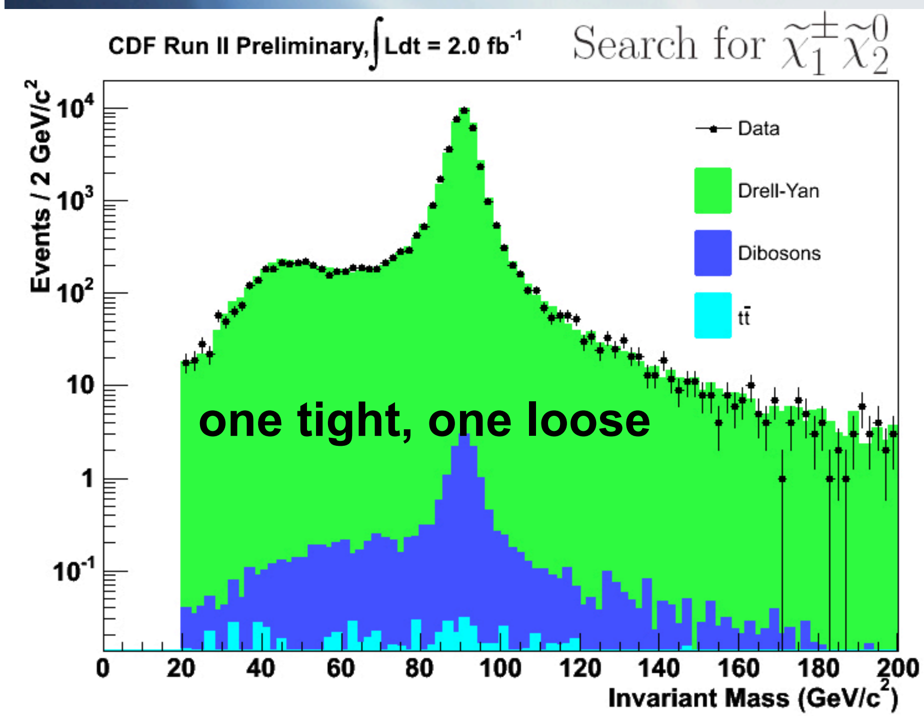


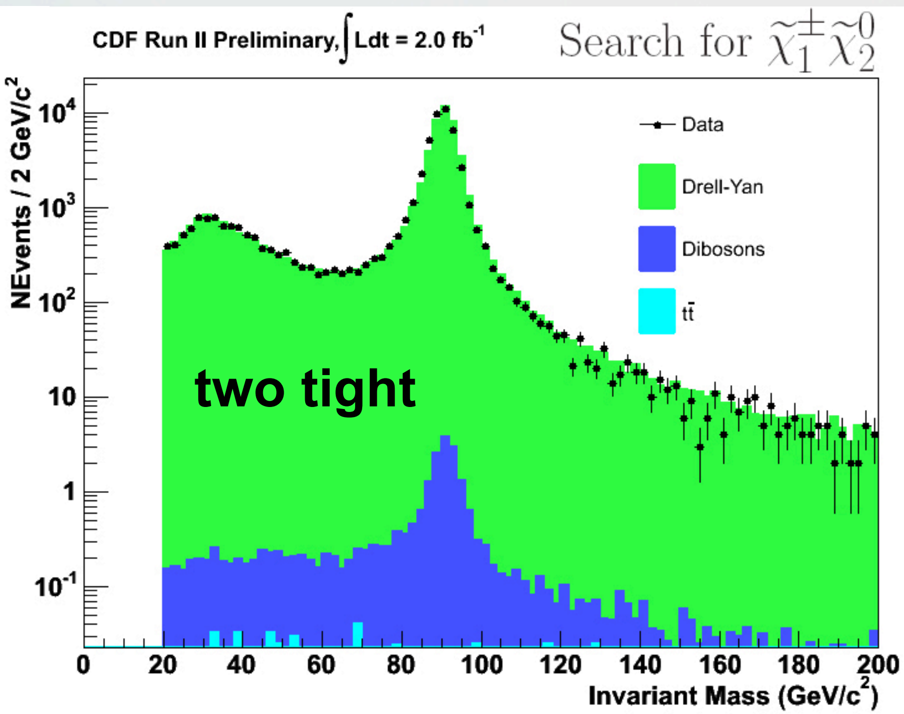


Control Regions : Dileptons



Breaking Dilepton Invariant Mass into **one tight, one loose** and **two tight**



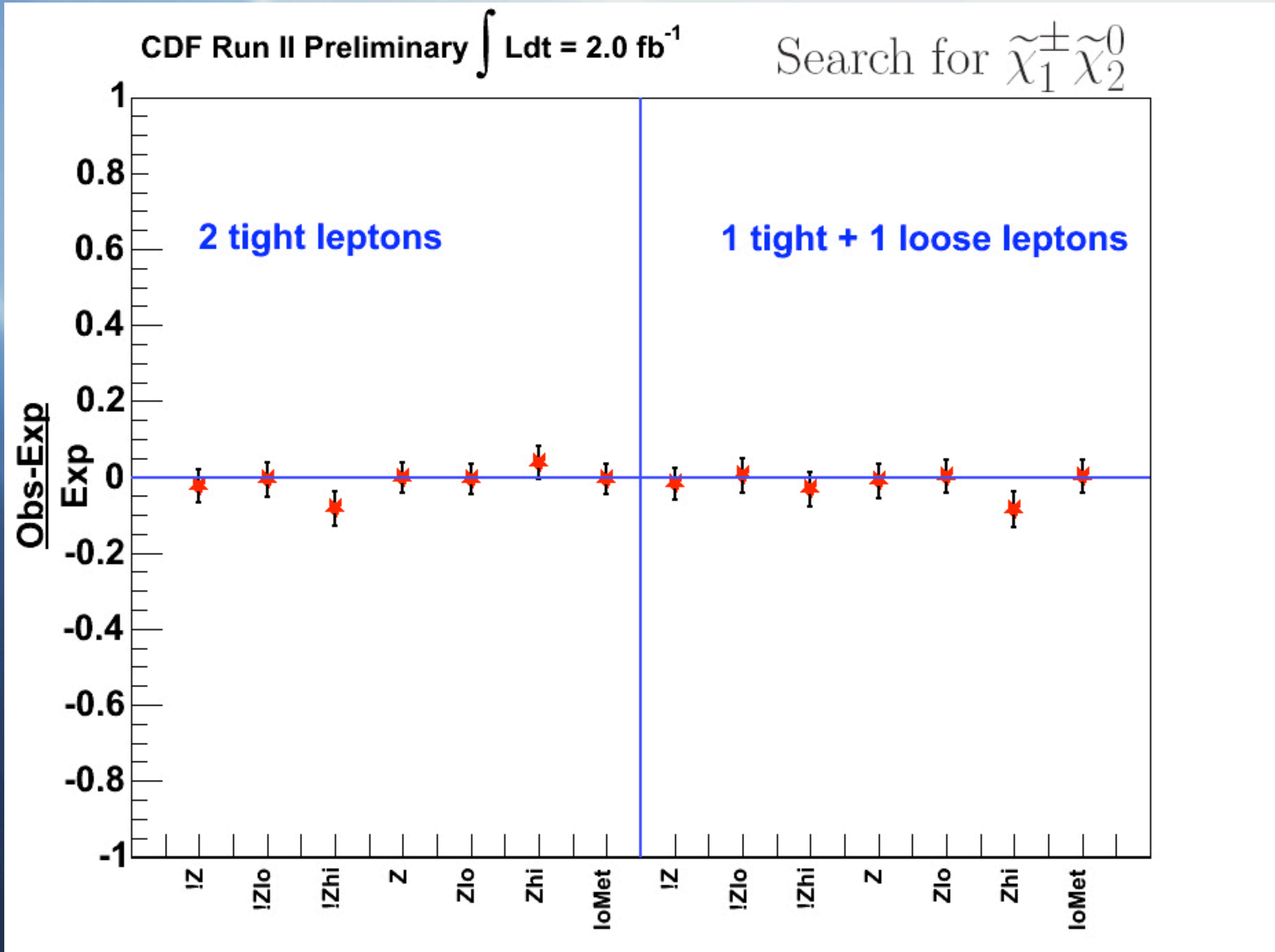


Control Regions : Dileptons

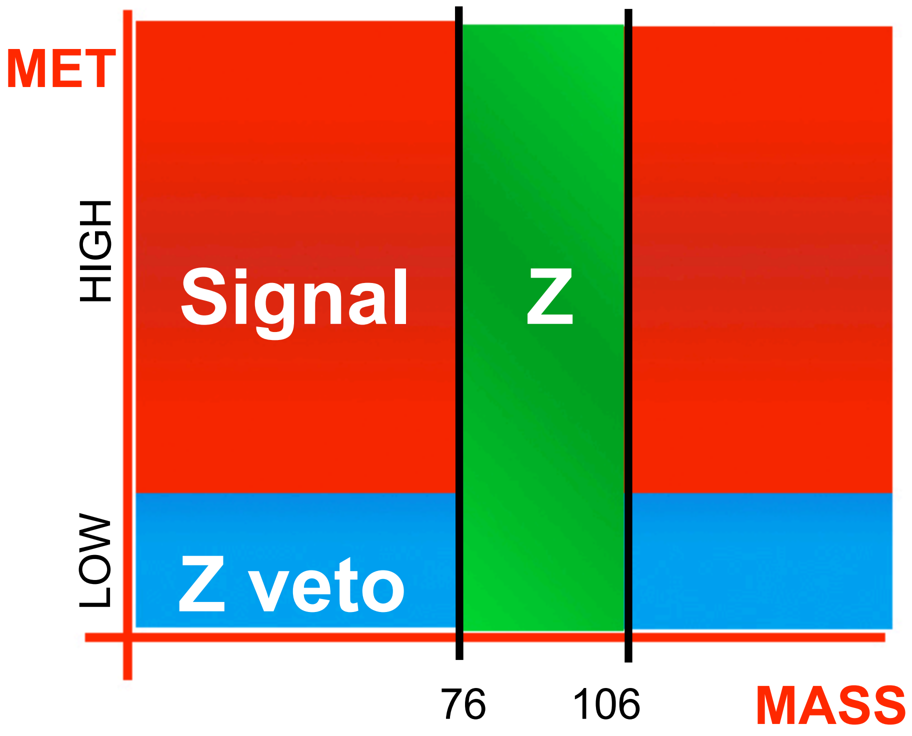
CDF RUN II Preliminary $\int \mathcal{L}dt = 2.0\ \mathrm{fb}^{-1}$: Search for $\tilde{\chi}_1^{\pm}\tilde{\chi}_2^0$

Name	Z$\rightarrow ee$	Z$\rightarrow \mu\mu$	Z$\rightarrow \tau\tau$	WW	WZ	ZZ	$t\bar{t}$	Expected	Observed
				2tight					
!Z	9847.8	5034.7	1310.2	93.3	1.6	7.1	57.1	16352 $\pm$ 716	15966
!Zlo	7705.6	4240.6	477.7	4.7	0.1	2.3	1.0	12432 $\pm$ 569	12352
!Zhi	858.4	205.5	550.3	83.5	1.4	3.6	55.0	1758 $\pm$ 80	1612
Z	31178.2	19870.4	21.9	22.4	6.3	35.8	15.0	51150 $\pm$ 2034	51042
Zlo	25577.6	16665.6	11.1	1.6	0.2	13.4	0.2	42270 $\pm$ 1682	42093
Zhi	1261.1	741.5	6.4	19.0	5.8	15.9	14.4	2064 $\pm$ 92	2143
lo	33349.6	20903.9	488.7	6.3	0.3	15.7	1.2	54766 $\pm$ 2212	54445
Z(ee)	31178.3	0.0	6.7	6.5	4.0	21.9	4.7	31222 $\pm$ 1710	31074
Z($\mu\mu$)	0.0	19867.7	3.9	4.6	2.3	13.9	3.0	19895 $\pm$ 1102	19942
!Z(ee)	9847.9	0.0	497.8	29.9	1.1	4.3	18.3	10399 $\pm$ 617	10033
!Z($\mu\mu$)	0.0	5015.4	243.2	18.2	0.4	2.3	10.9	5290 $\pm$ 352	5198
$e\mu$	0.0	21.9	580.4	56.5	0.1	0.5	35.1	694 $\pm$ 47	761

Control Regions : Dileptons



Ready for 3 Leptons



High MET, Z-veto is now signal box

Use Z events to test MET

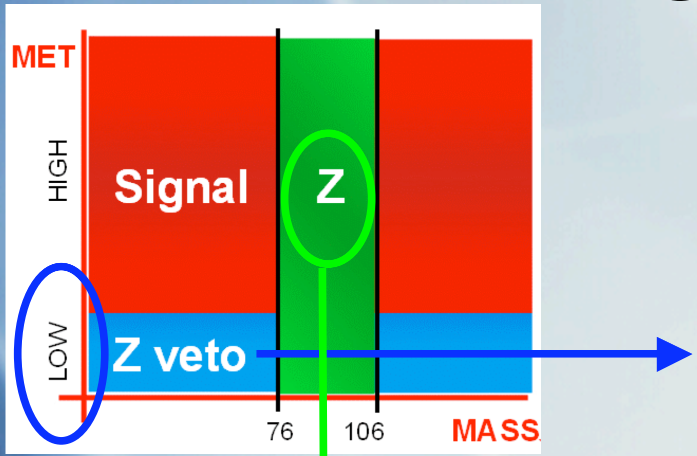
Use high MET Z region to test dibosons (WZ,WW)

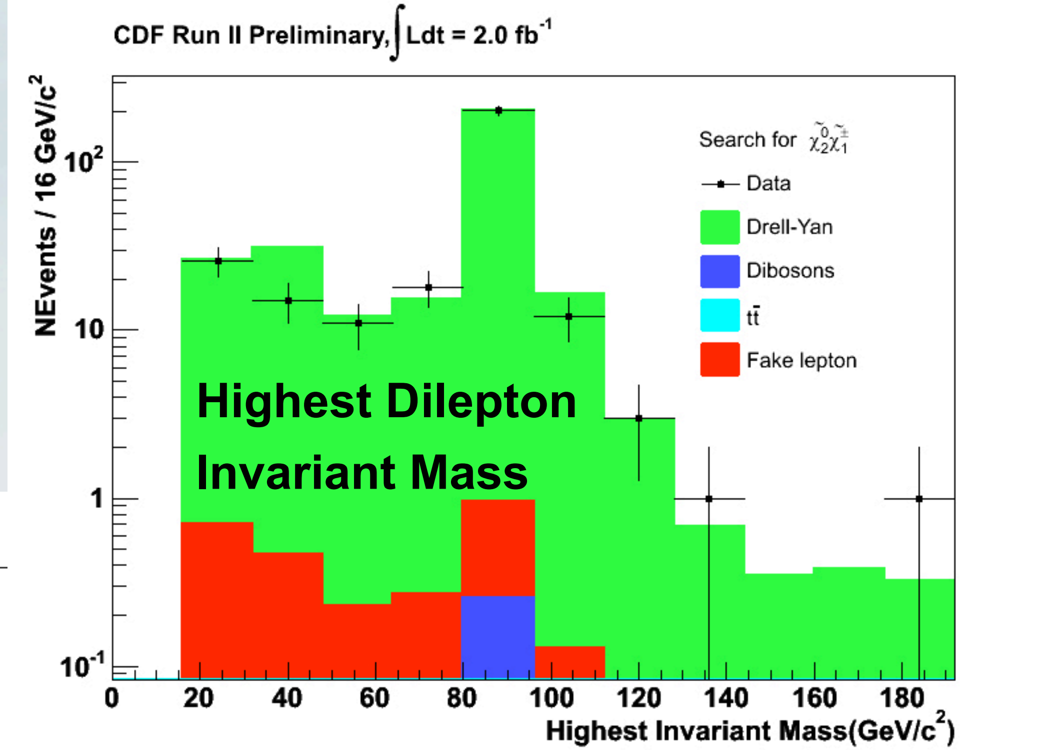
Test 'fake' estimations in

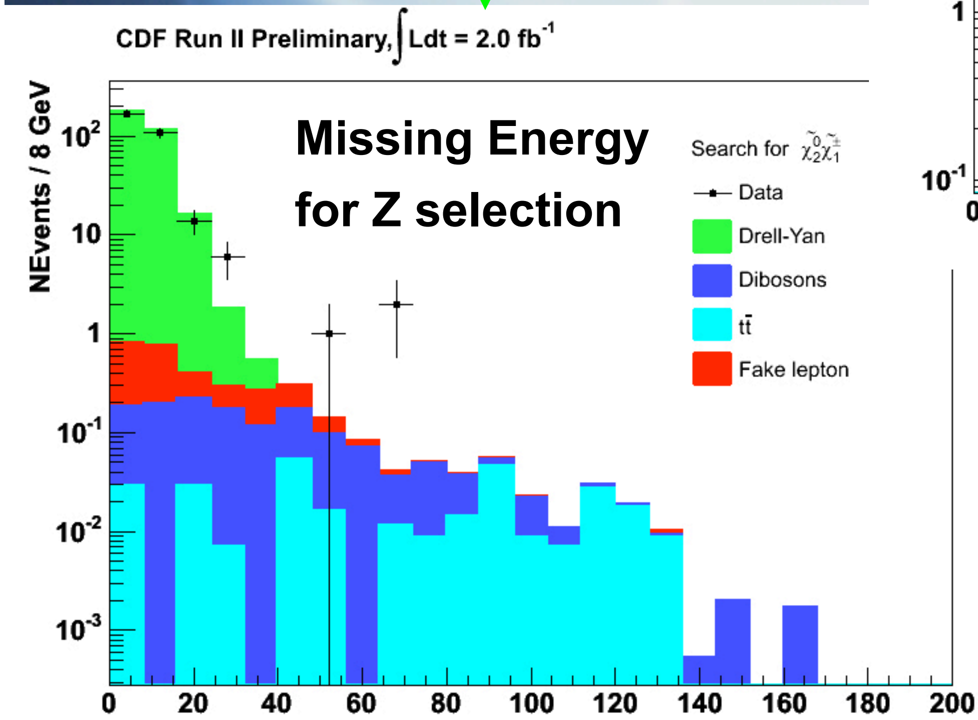
- ✓ Z events and low-mass,
- ✓ low-MET events.

Trileptons = two opposite charge pairs. Take higher to define control regions.

Control Regions : Trileptons



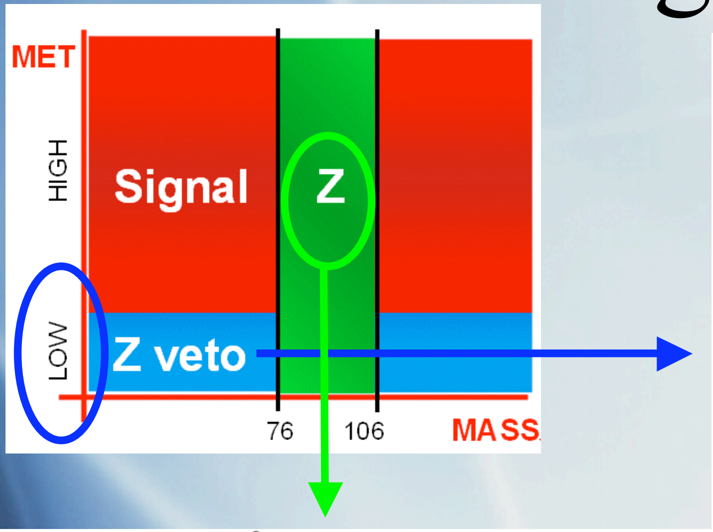


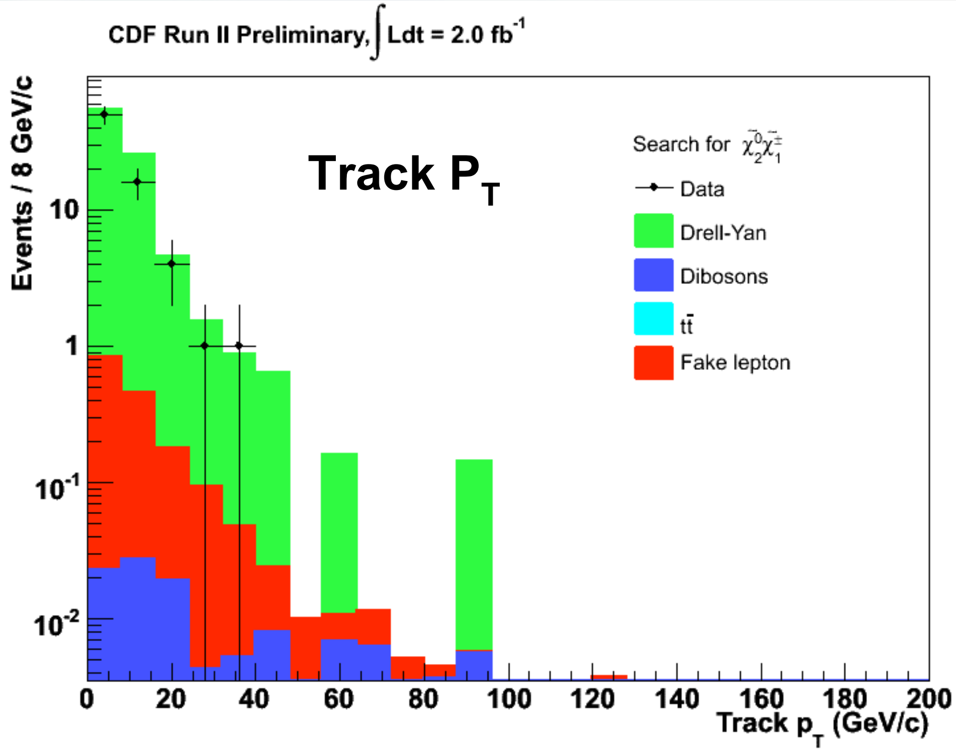


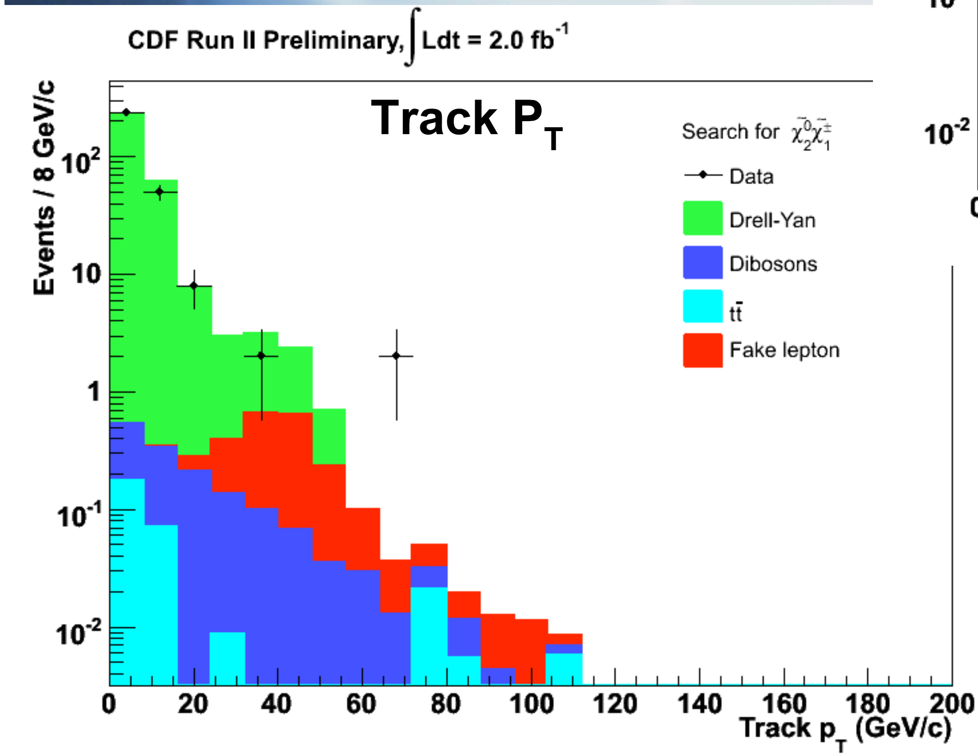
Selection :

2 tight leptons + 1 Track

Control Regions : Trileptons



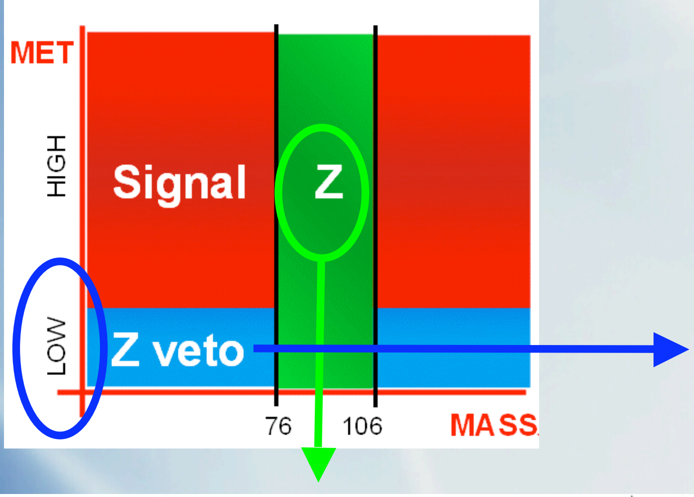


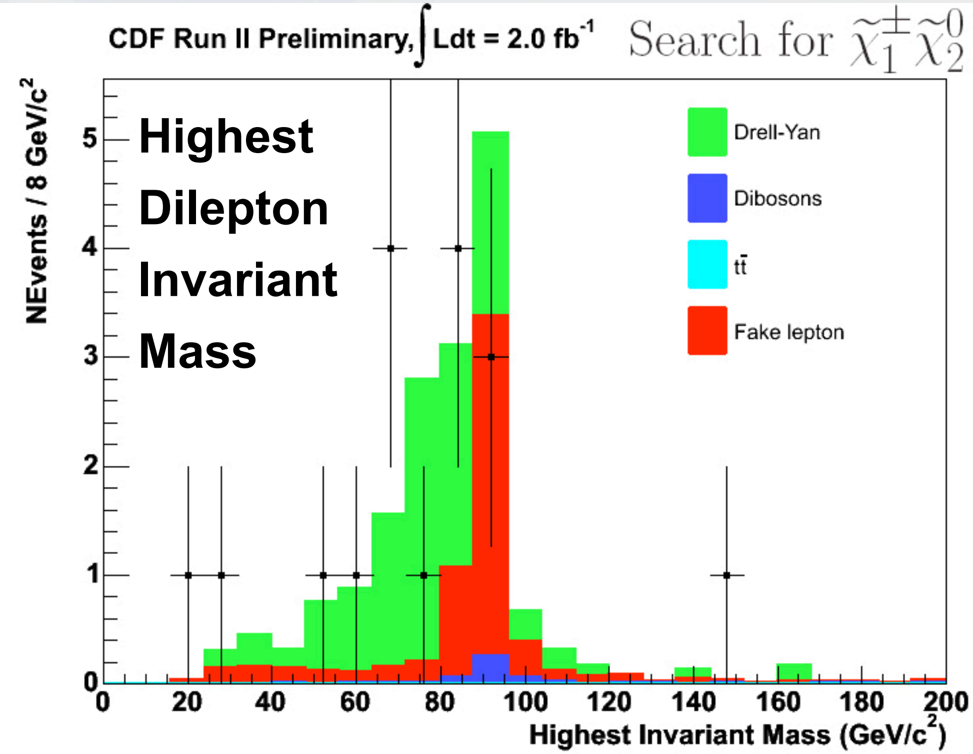


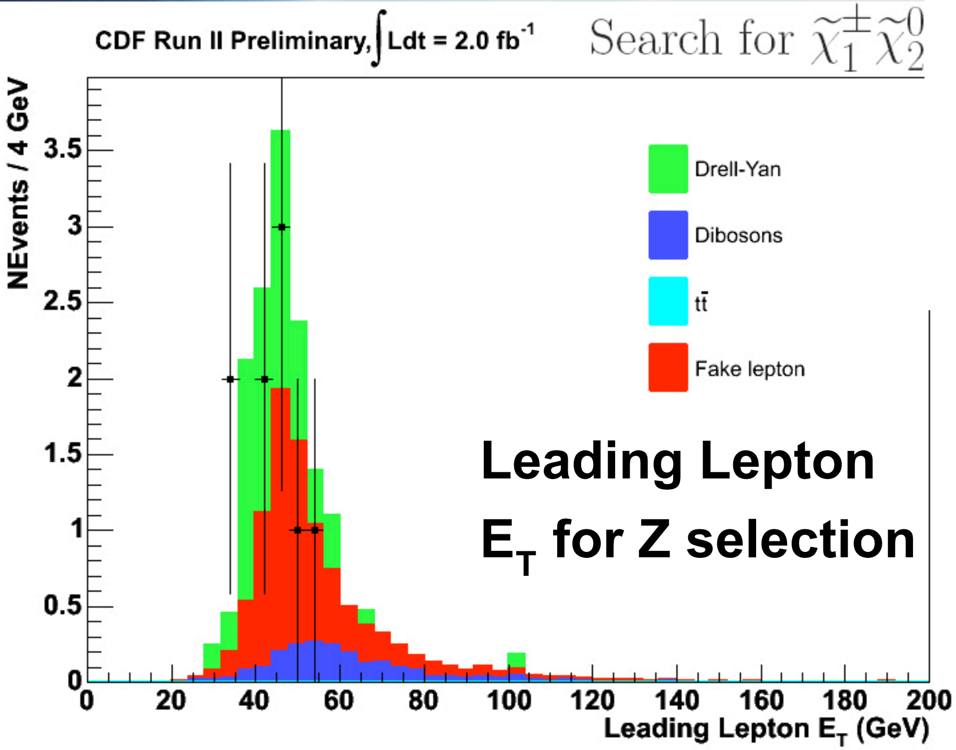
Selection :

2 tight leptons + 1 Track

Control Regions : Trileptons



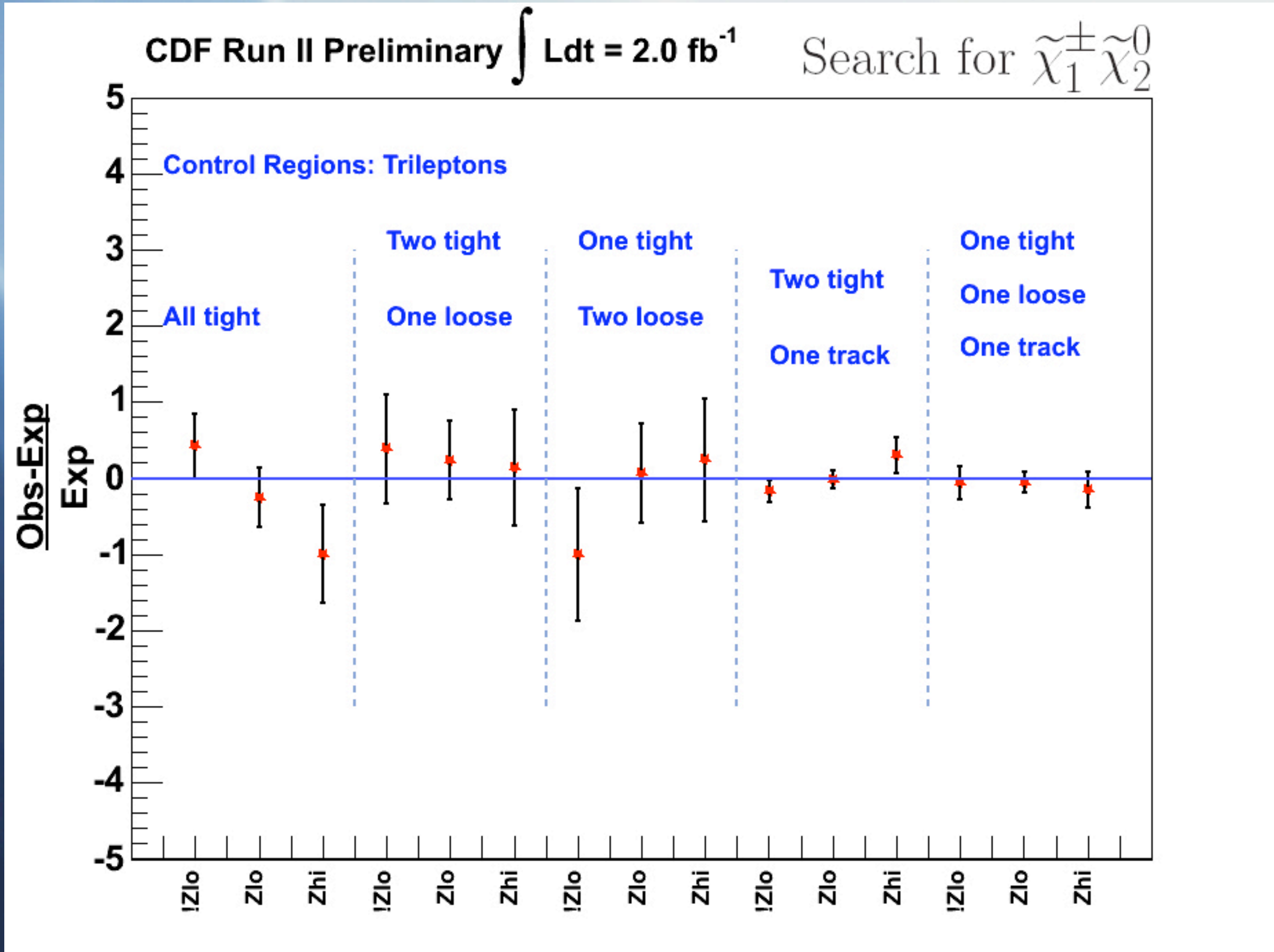




Selection :

3 Tight Leptons

Control Regions : Trileptons



Control Region Summary

- ✓ There are ~50 (dilepton+trilepton) control regions. This is where we spent most time and effort!
- ✓ Observed and predicted events are consistent within statistical fluctuations

→ Ready to open the Signal Box

FINAL PREDICTIONS

CDF Run II Preliminary, $\int L dt = 2.0\ \mathrm{fb}^{-1}$

Channel	Signal	Background	Observed
3 tight	2.3 ±0.1 ±0.3	0.5 ±0.04 ±0.1	
2 tight 1 loose	1.6 ±0.1 ±0.2	0.3 ±0.03 ±0.03	
1 tight 2 loose	0.7 ±0.1 ±0.1	0.1 ±0.02 ±0.02	
Total trilepton	4.6 ±0.2 ±0.6	0.9 ±0.1 ±0.2	
2 tight 1 track	4.4 ±0.2 ±0.6	3.2 ±0.5 ±0.5	
1 tight 1 loose 1 track	2.4 ±0.1 ±0.3	2.3 ±0.5 ±0.4	
Total dilepton+track	6.8 ±0.2 ±0.9	5.5 ±0.7 ±0.9	

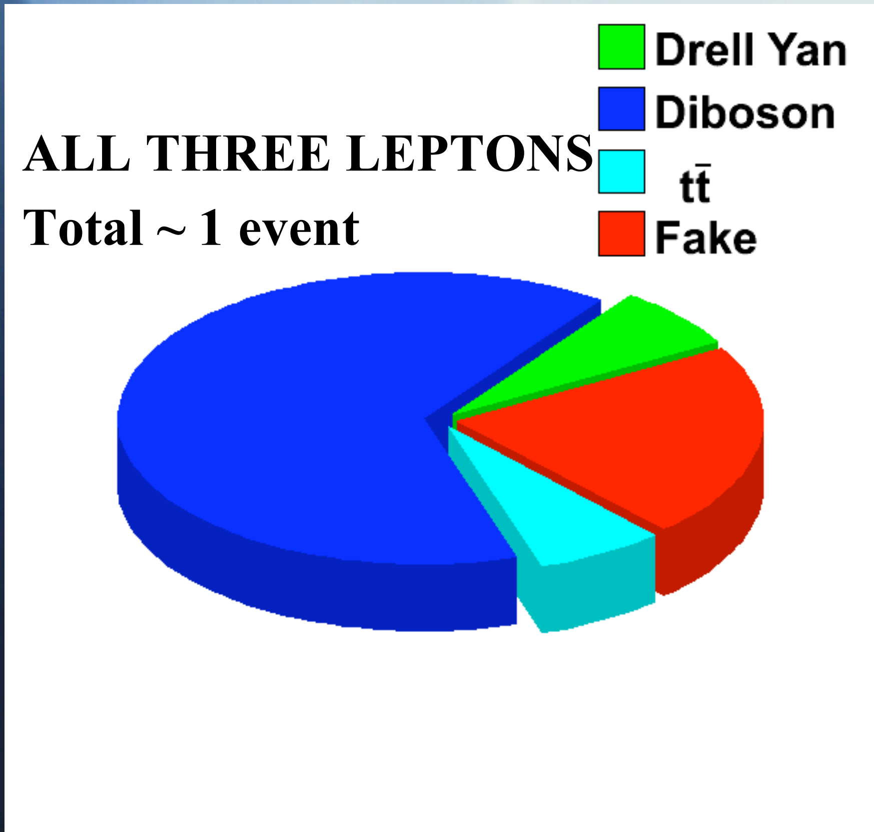
TOTAL EXPECTED SIGNAL = 11.4 events

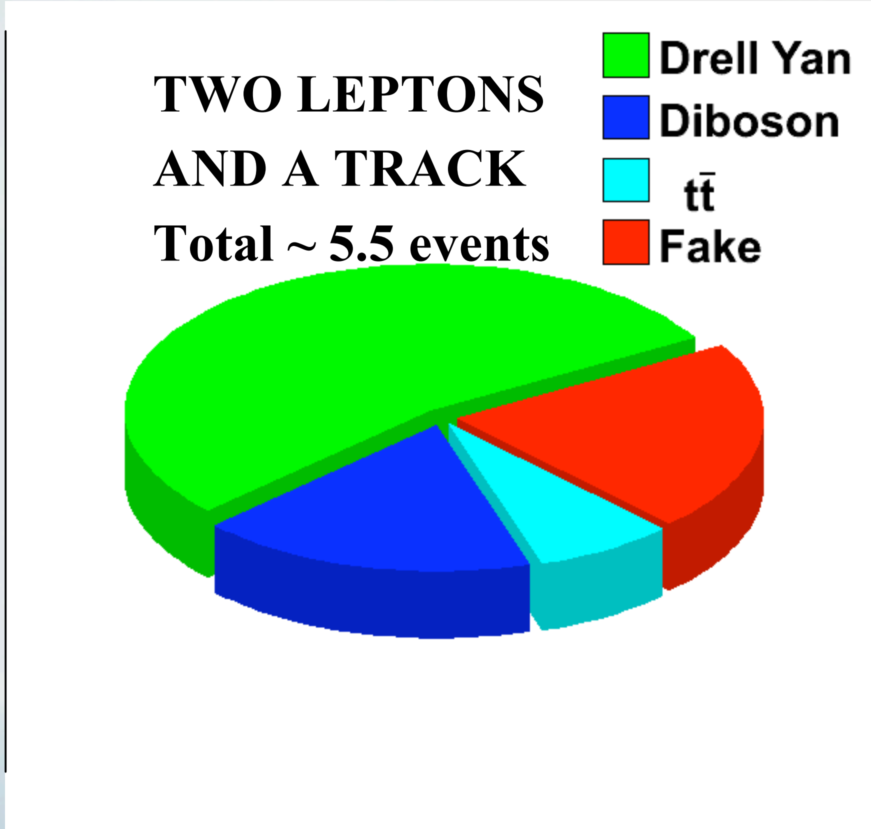
Signal : mSUGRA $m_0=60$, $m_{1/2}=190$, $\tan(\beta)=3$, $A_0=0$, $\mu>0$, $M(\chi_1^{\pm})=120\ \mathrm{GeV}/c^2$

FINAL PREDICTIONS

Breakdown of Backgrounds

CDF Run II Preliminary, $\int Ldt = 2.0\ fb^{-1}$





Systematic Uncertainties

Backgrounds

Hadrons faking leptons &

underlying event $\longrightarrow$ tracks ~10%

Lepton identification ~ 2%

Jet energy scale ~ 2 to 5 %

Process Cross-section ~ 2 to 5%

Signal

Signal cross section ~ 10%

Lepton identification ~ 4%

Initial/Final State radiation ~ 4%

Common to both:

Luminosity ~ 6% and PDF ~ 2%

FINAL PREDICTIONS

CDF Run II Preliminary, $\int Ldt = 2.0\ fb^{-1}$

Channel	Signal	Background	Observed
3 tight	2.3 ±0.1 ±0.3	0.5 ±0.04 ±0.1	
2 tight 1 loose	1.6 ±0.1 ±0.2	0.3 ±0.03 ±0.03	
1 tight 2 loose	0.7 ±0.1 ±0.1	0.1 ±0.02 ±0.02	
Total trilepton	4.6 ±0.2 ±0.6	0.9 ±0.1 ±0.2	
2 tight 1 track	4.4 ±0.2 ±0.6	3.2 ±0.5 ±0.5	
1 tight 1 loose 1 track	2.4 ±0.1 ±0.3	2.3 ±0.5 ±0.4	
Total dilepton+track	6.8 ±0.2 ±0.9	5.5 ±0.7 ±0.9	

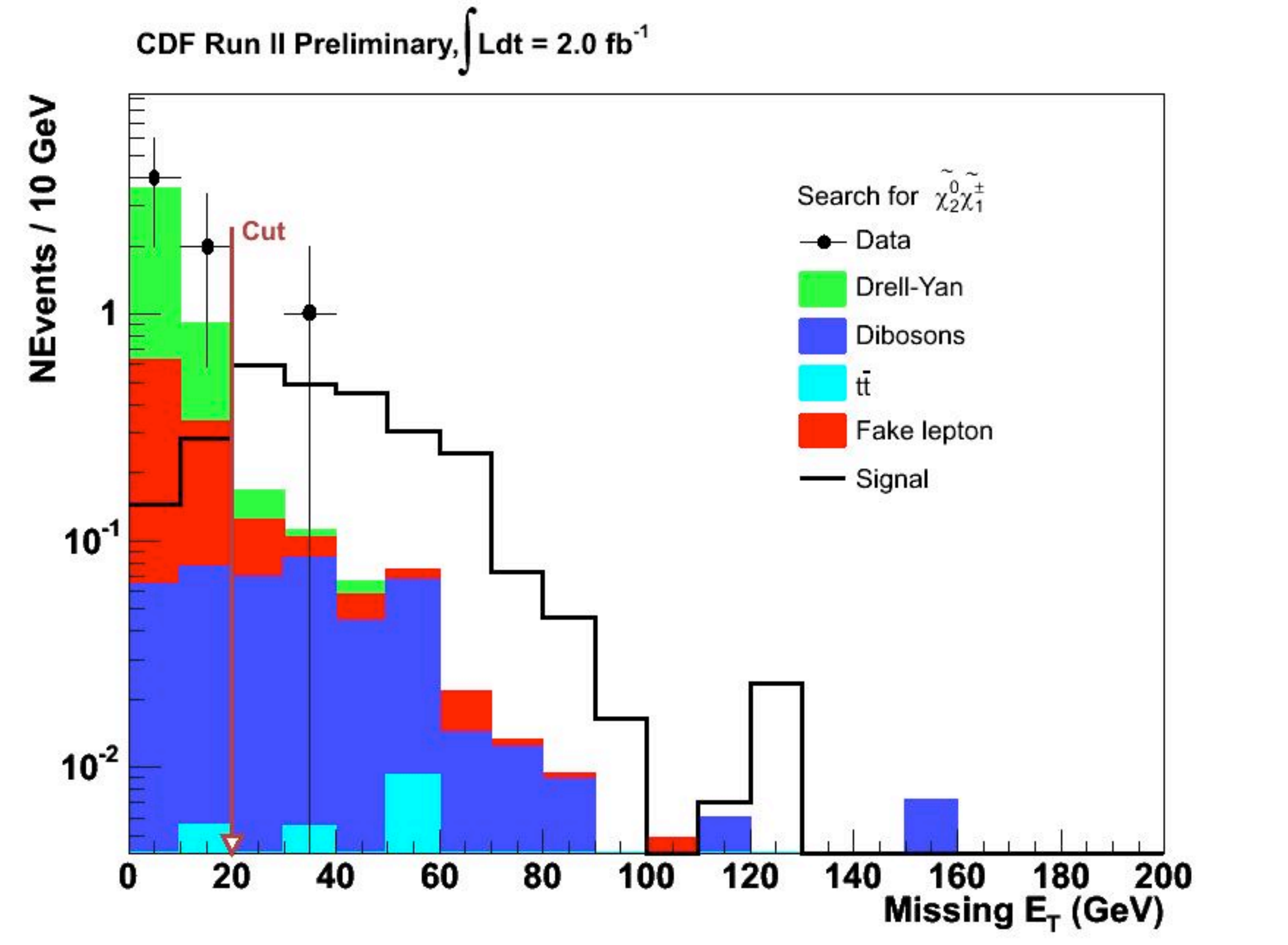
FINAL PREDICTIONS

CDF Run II Preliminary, $\int Ldt = 2.0\ fb^{-1}$

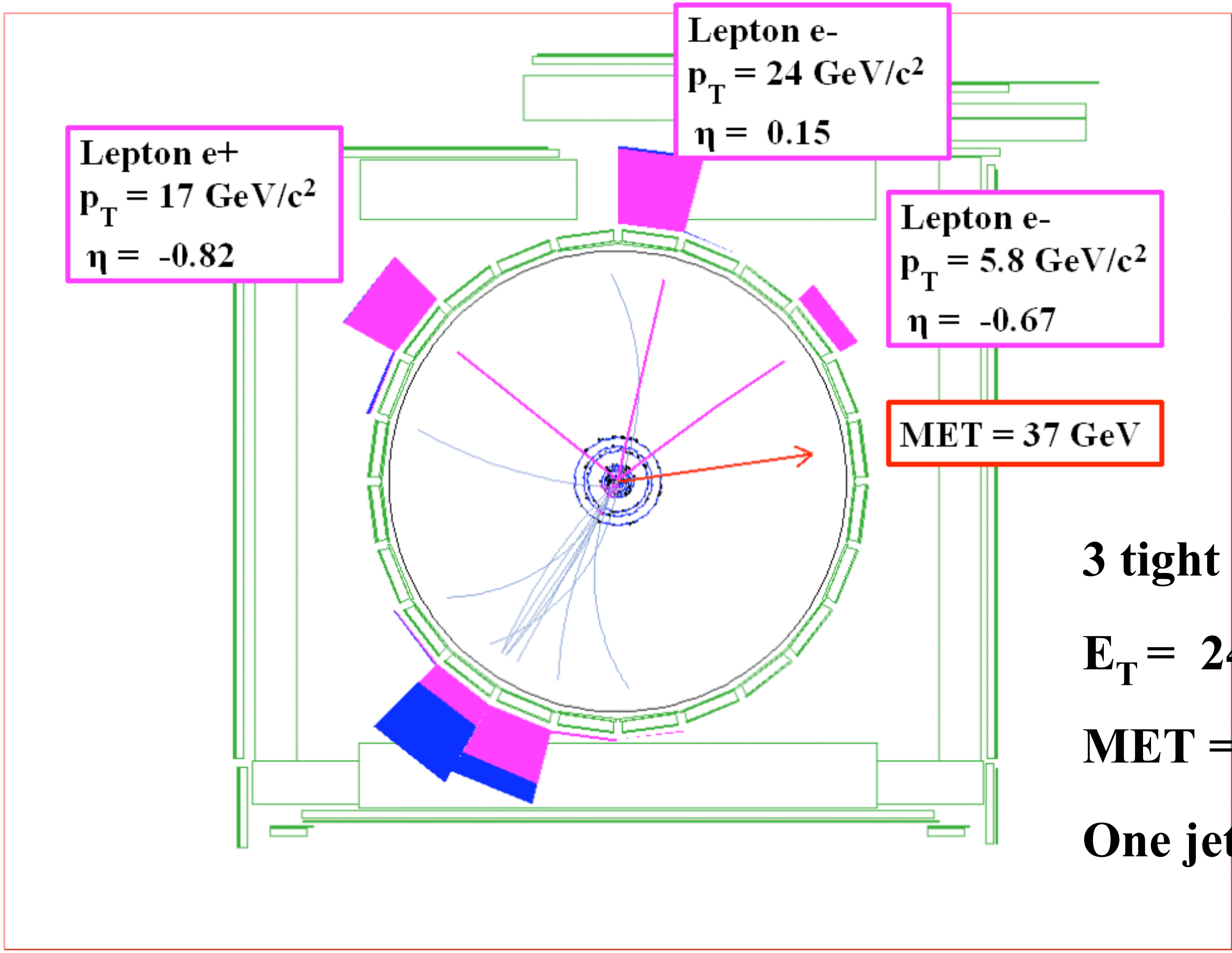
Channel	Signal	Background	Observed
3 tight	2.3 ±0.1 ±0.3	0.5 ±0.04 ±0.1	1
2 tight 1 loose	1.6 ±0.1 ±0.2	0.3 ±0.03 ±0.03	0
1 tight 2 loose	0.7 ±0.1 ±0.1	0.1 ±0.02 ±0.02	0
Total trilepton	4.6 ±0.2 ±0.6	0.9 ±0.1 ±0.2	1

Missing E_T

3 tight → 1 event



3 Tight Lepton Event



3 tight electron event

E_T = 24 , 17 , 6 GeV

MET = 37 GeV

One jet, Jet E_T = 60 GeV

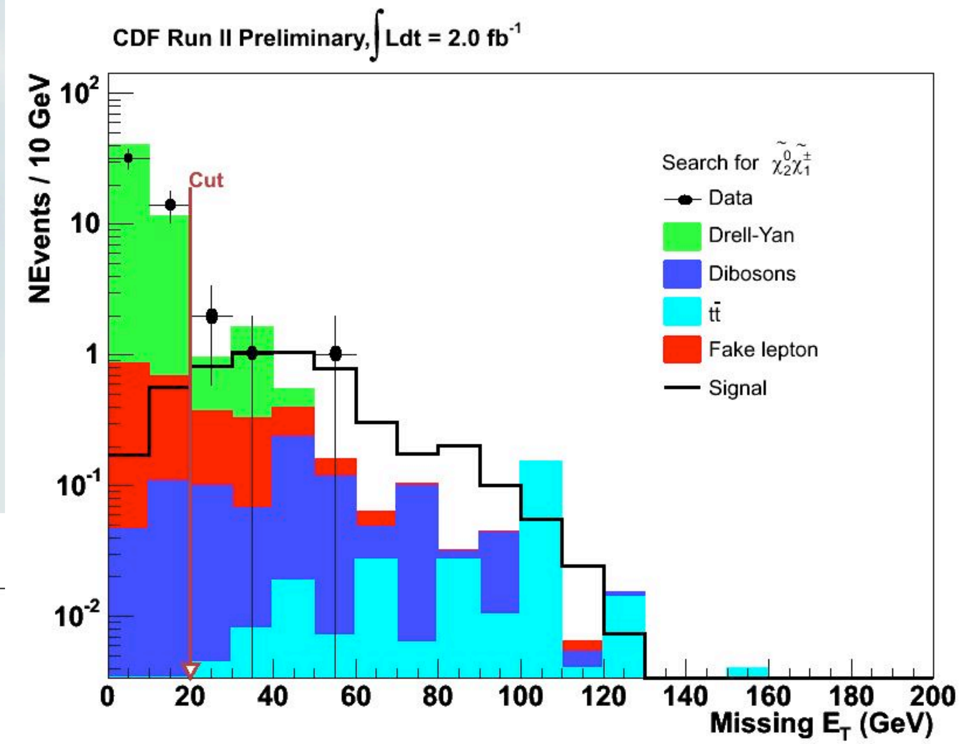
FINAL PREDICTIONS

CDF Run II Preliminary, $\int Ldt = 2.0\ fb^{-1}$

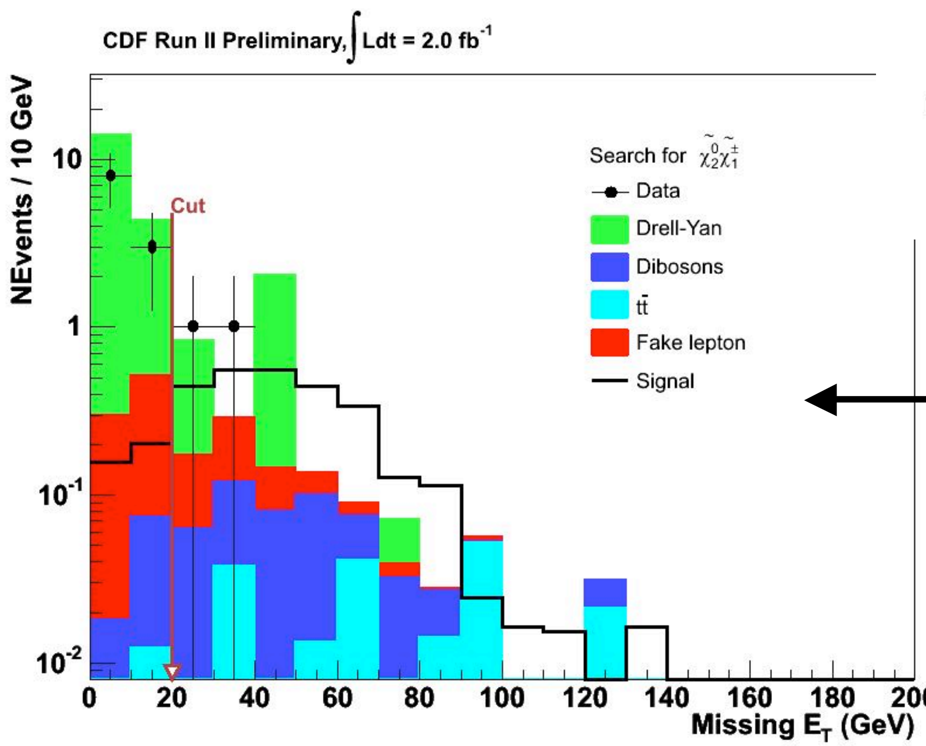
Channel	Signal	Background	Observed
3 tight	2.3 ±0.1 ±0.3	0.5 ±0.04 ±0.1	1
2 tight 1 loose	1.6 ±0.1 ±0.2	0.3 ±0.03 ±0.03	0
1 tight 2 loose	0.7 ±0.1 ±0.1	0.1 ±0.02 ±0.02	0
Total trilepton	4.6 ±0.2 ±0.6	0.9 ±0.1 ±0.2	1
2 tight 1 track	4.4 ±0.2 ±0.6	3.2 ±0.5 ±0.5	4
1 tight 1 loose 1 track	2.4 ±0.1 ±0.3	2.3 ±0.5 ±0.4	2
Total dilepton+track	6.8 ±0.2 ±0.9	5.5 ±0.7 ±0.9	6

Missing E_T

2 tight, 1 Track → 4 events



1 tight, 1 loose, 1 Track → 2 events

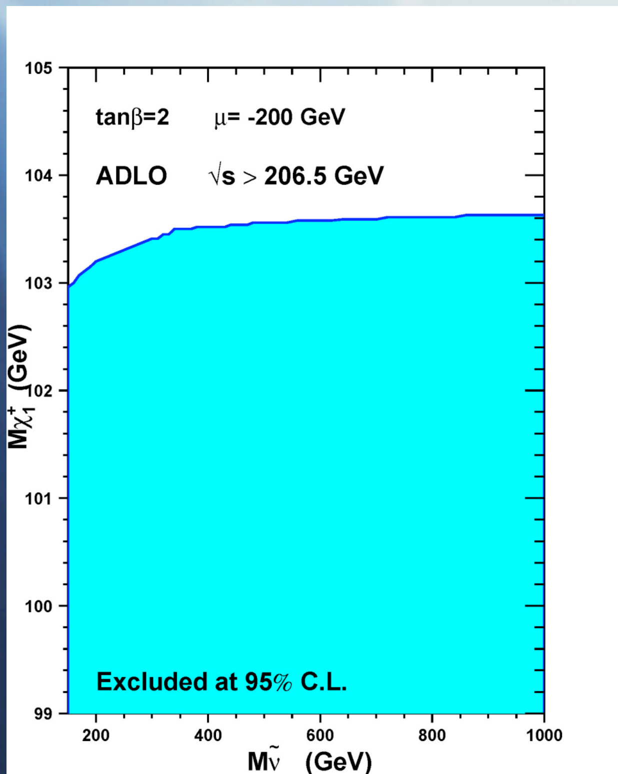


Interpreting the results

Present State of Knowledge

<u>LEP result</u> is model independent

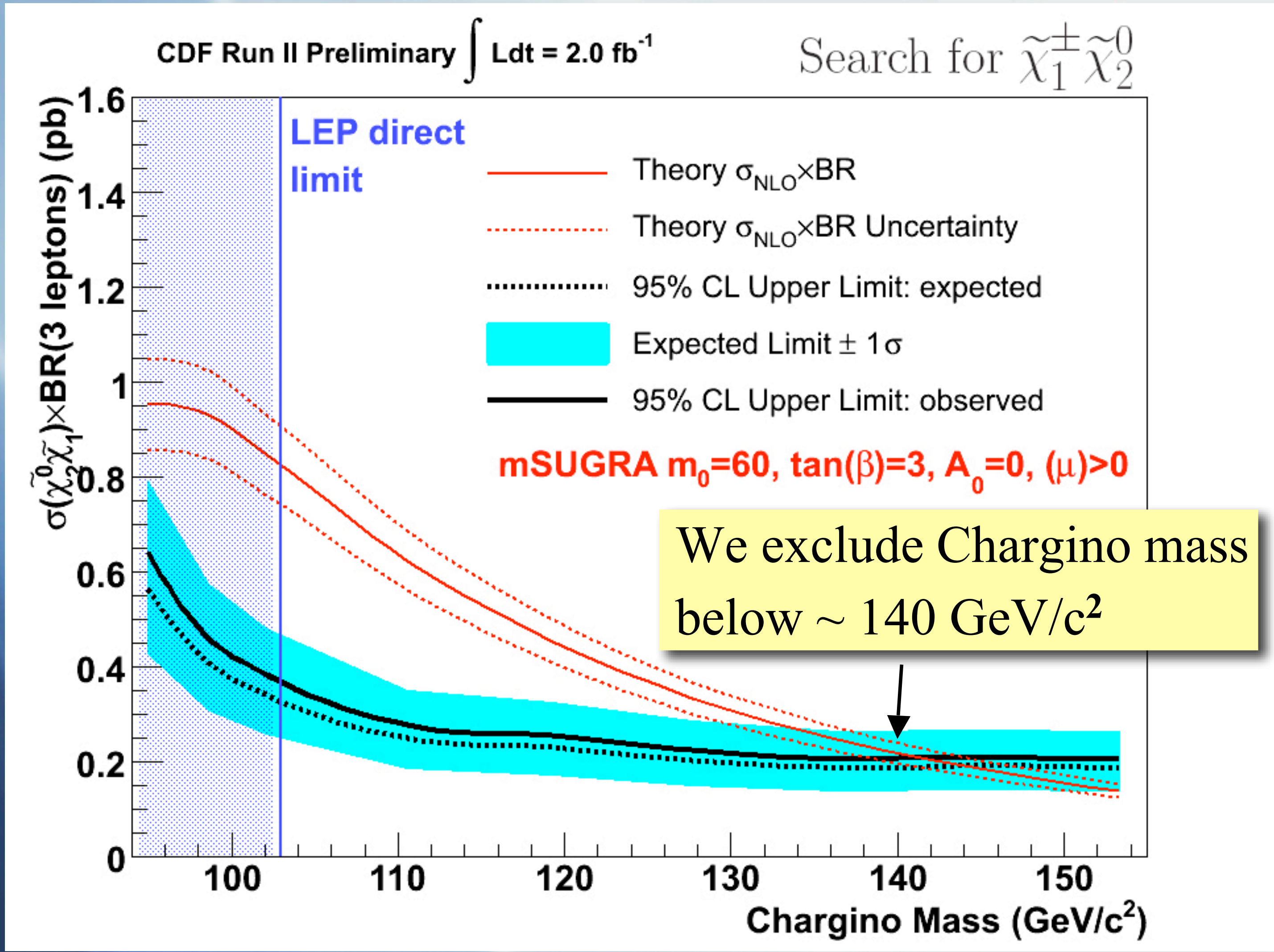
Mass (chargino) > 103.5 GeV/c^2



We can place limits on σxBR as a function of mass of the particle

-- we exclude SUSY particles with masses below a threshold at 95% C.L. --

First mSUGRA Direct Limits since LEP!



Improvements since 1 fb^{-1}

Expected limit improved 122 to 142 GeV/c^2

Observed limit : No exclusion before...

Now excluding ~140 GeV/c^2

Now with 2 fb^{-1}

✓ We have a unified search method –
all channels for all lepton flavors in parallel.

✓ Channels are defined exclusively –
thus combining channels is straightforward.

✓ We added new categories of events such as
dimuon+track to previous set.

⇒ Being systematic allowed better optimization of selection

Conclusions and outlook

Conclusions and Outlook

- We analyzed 2 fb^{-1} of 1.96 TeV $p\bar{p}$ collisions at CDF
- For our benchmark mSUGRA parameters, we expected ~12 SUSY events
- The observation of 7 events is consistent with the Standard Model expectation of 6.4 events

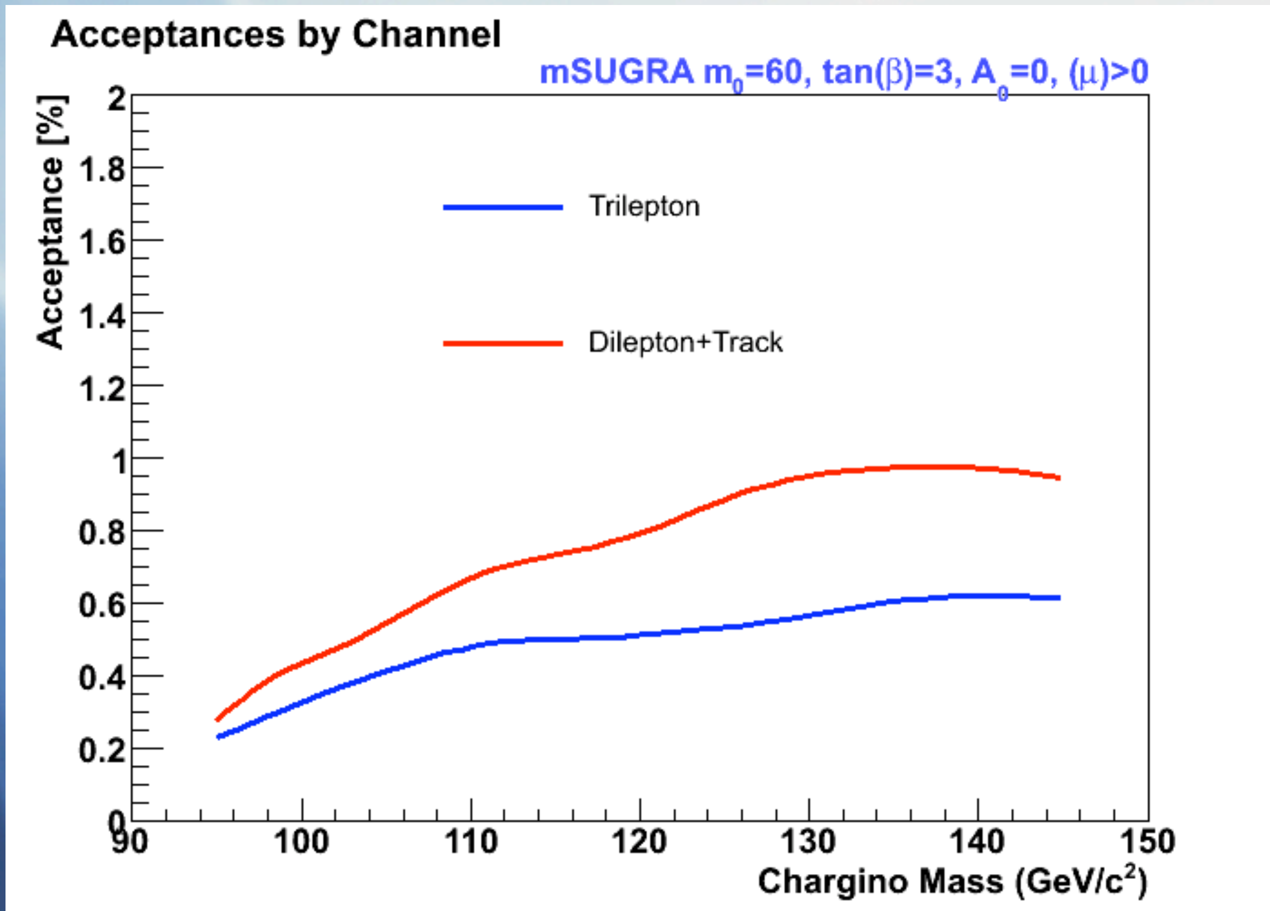
- We set limits on mSUGRA Chargino mass well beyond LEP
- We are working on interpreting results to reduce model dependence

- CDF has a trilepton analysis in place – more data now ready to be analyzed to probe other regions in mSUGRA, and other models

….. the hunt for SUSY continues.…

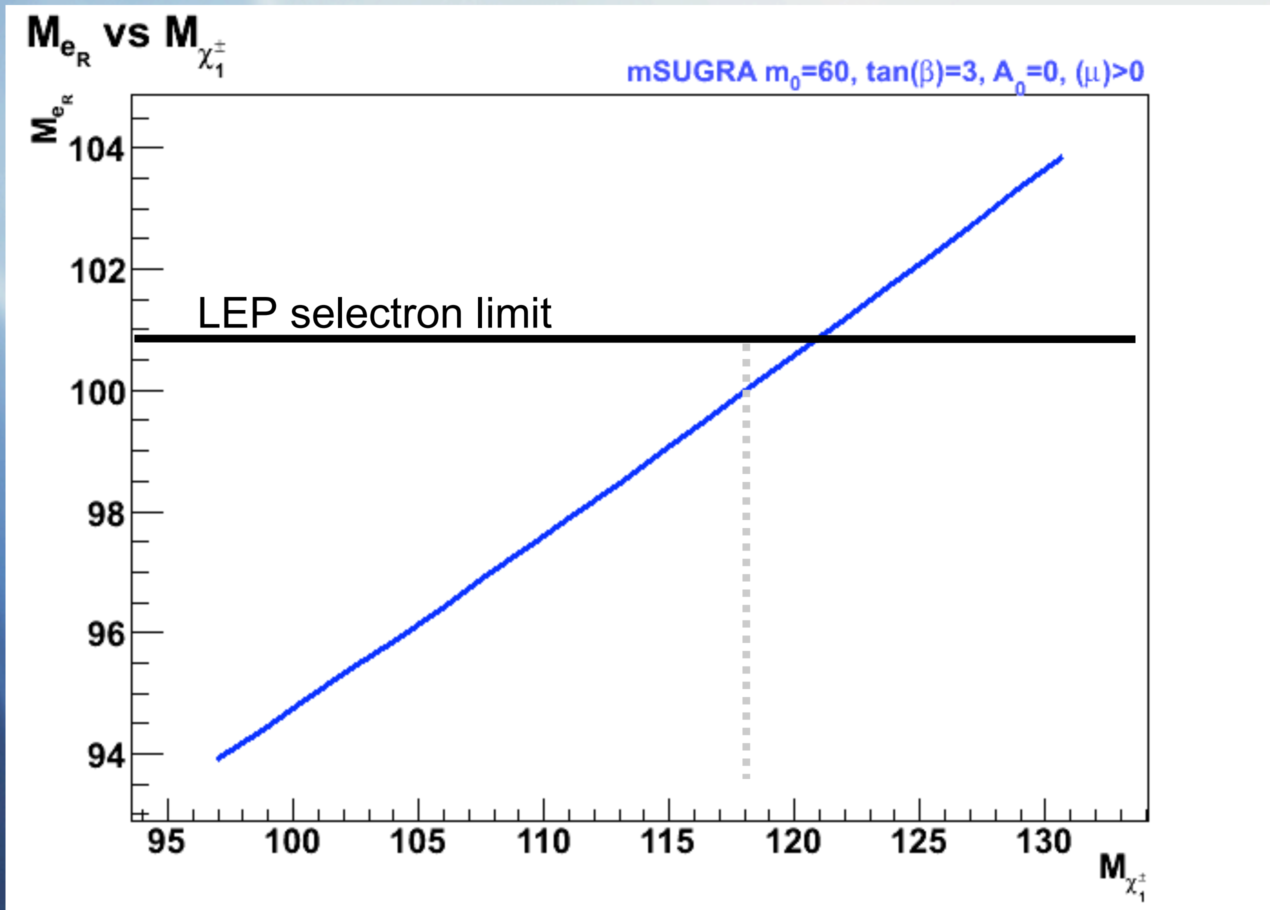
Back-up slides

Signal Plots : Acceptances by Channel

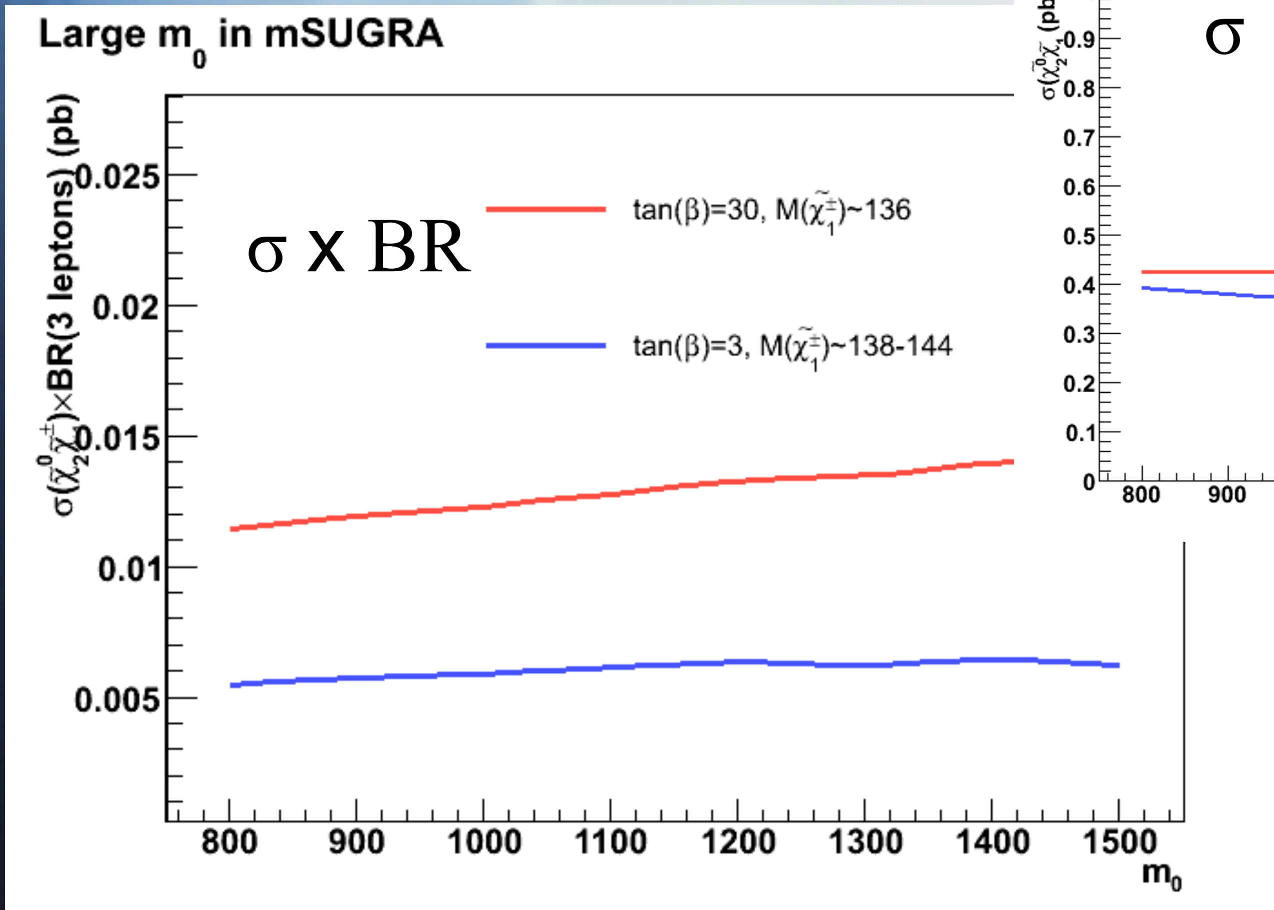


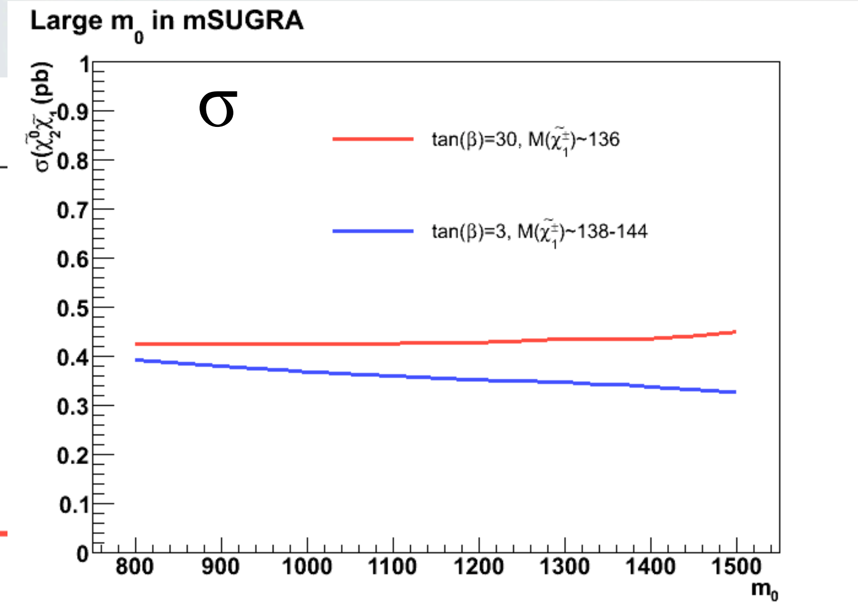
Signal Plots

M(selectron) vs M(chargino)



Signal Plots : Large m_0



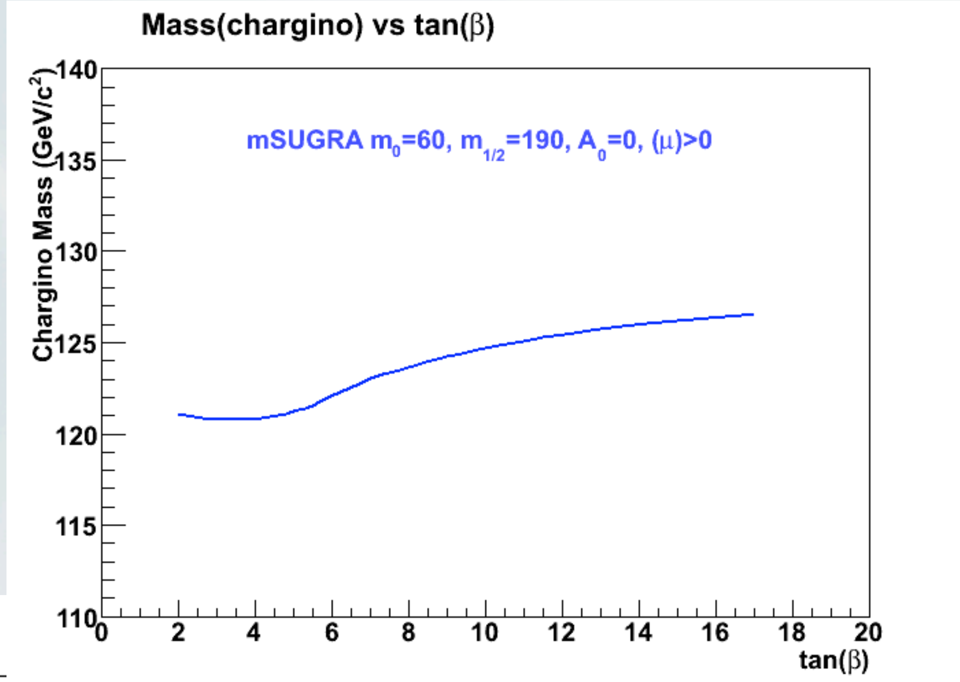


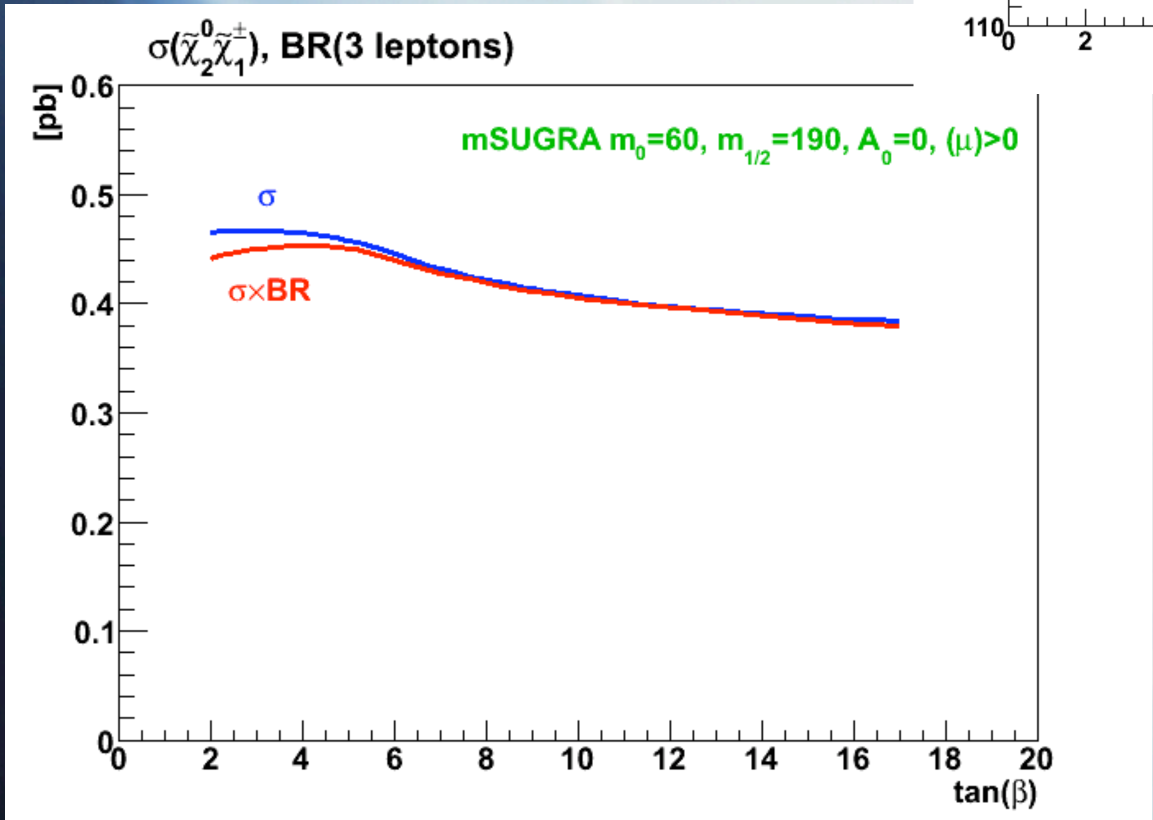
$\tan(\beta) = 30$

$\tan(\beta) = 3$

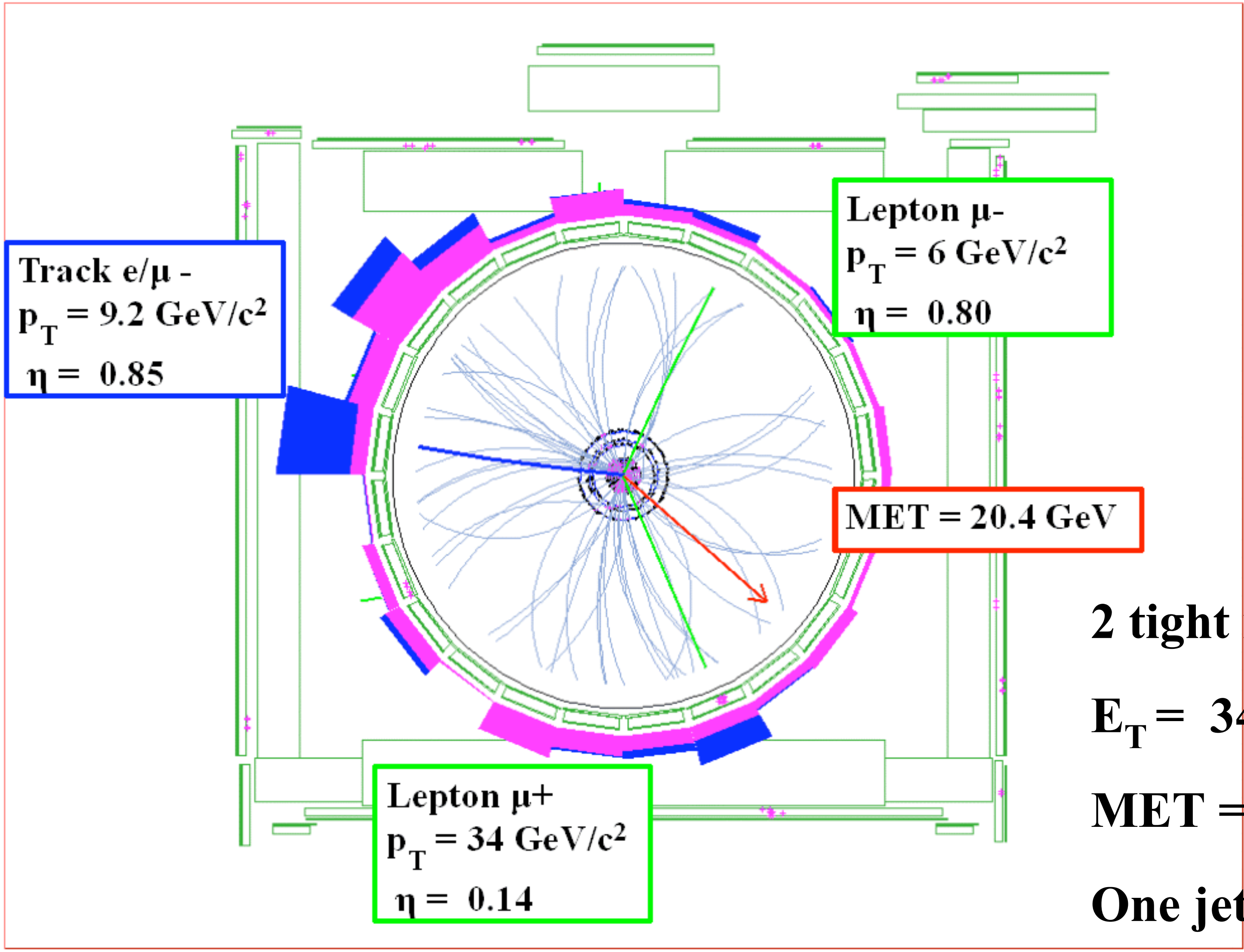
$m_{1/2} = 190$, $A_0 = 0$, $\mu > 0$

Signal Plots
tan(β) variation





EVENTS



2 tight muons + 1 Track

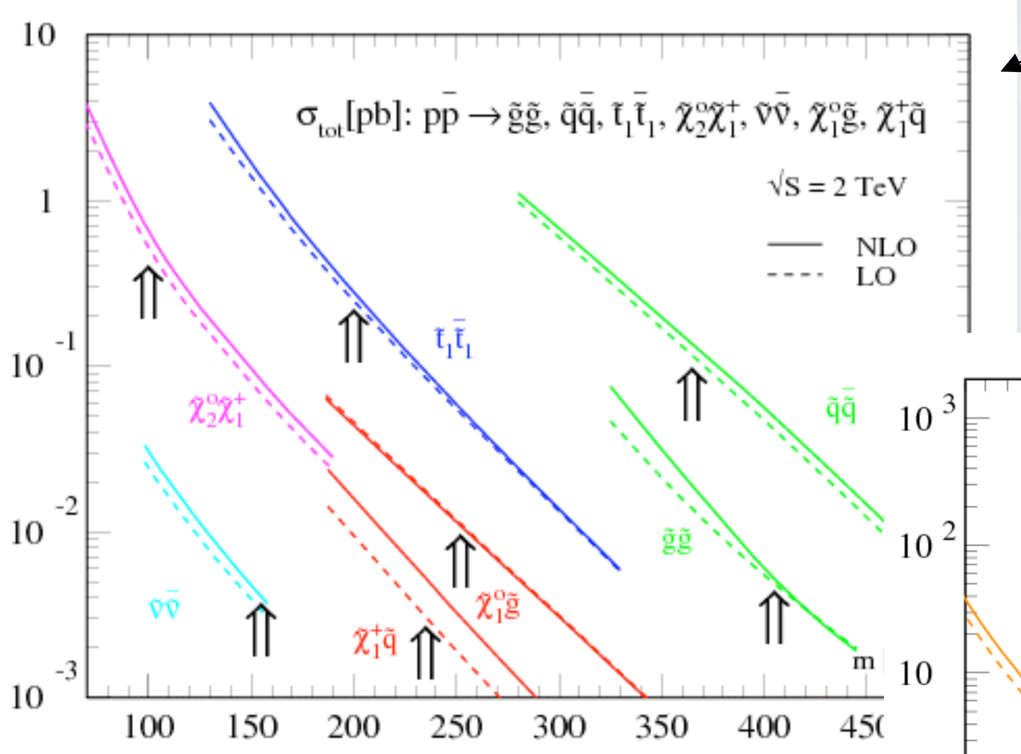
E_T = 34 , 6 , 9 GeV

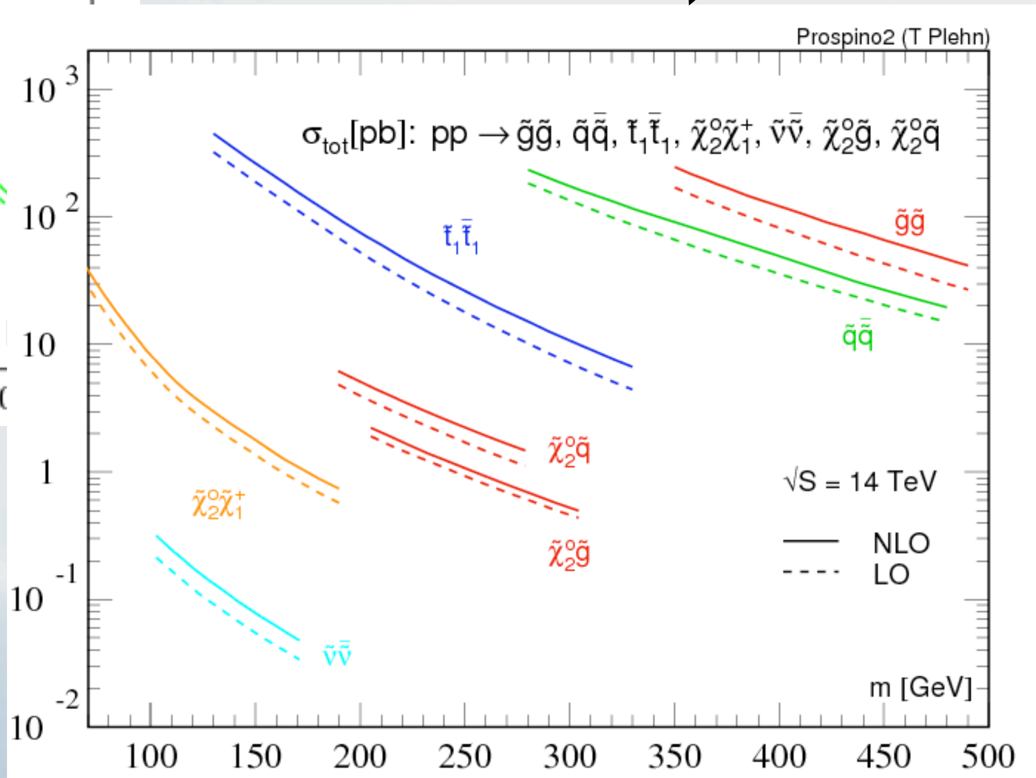
MET = 20.4 GeV

One jet, Jet E_T = 22 GeV

Cross Sections : Tevatron & LHC

T. Plehn, PROSPINO

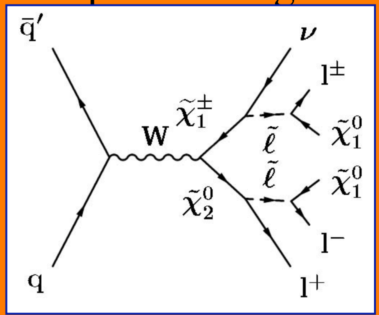




mSUGRA “small m_0”

$M(\tilde{\ell}) > M(\tilde{\chi}_2^0)$

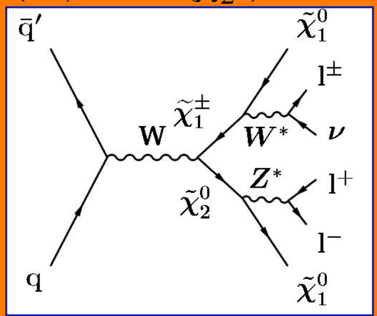
No slepton mixing



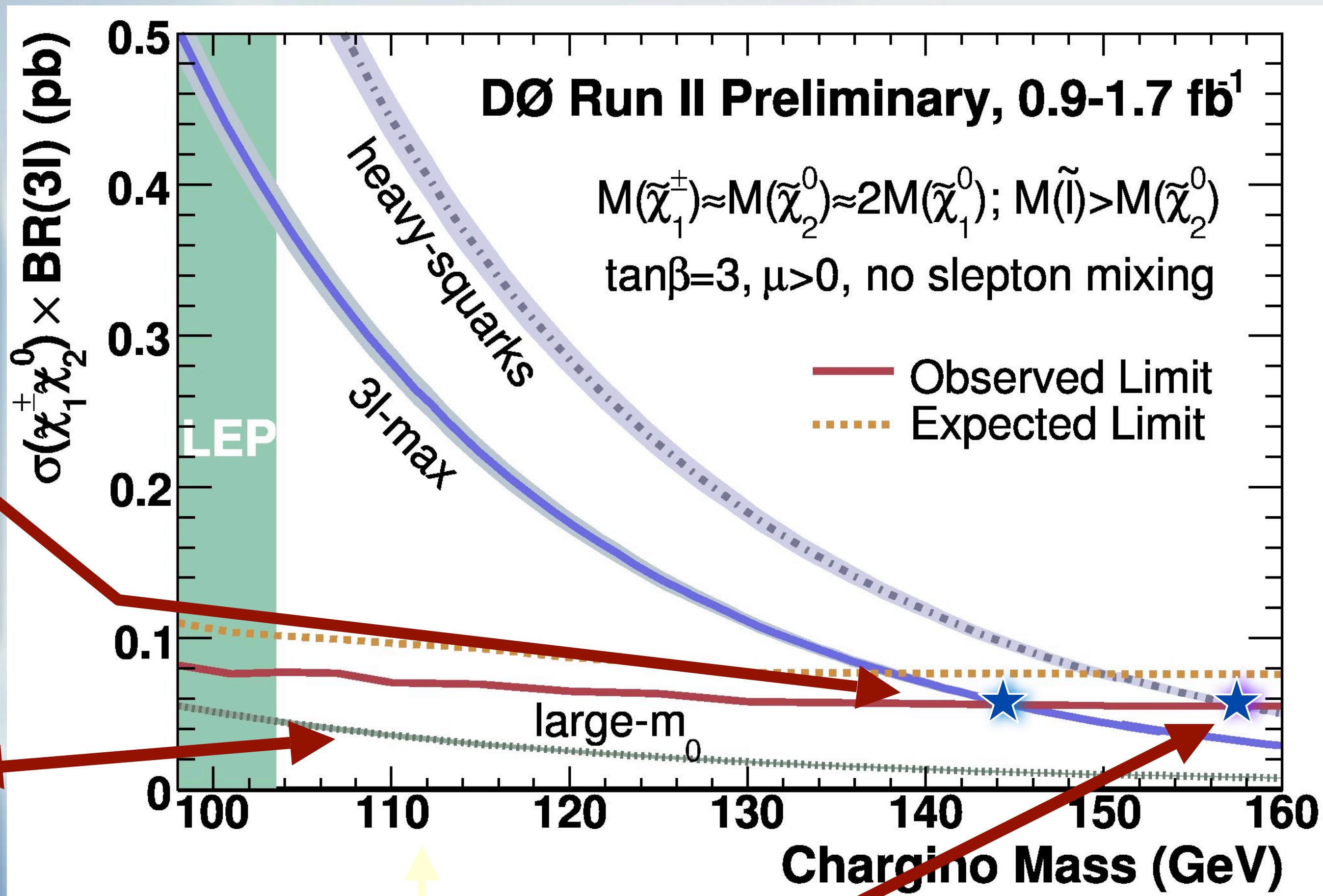
➢ $\sigma \times BR < 0.2$ pb

mSUGRA “large m_0”

$M(\tilde{\ell}) \gg M(\tilde{\chi}_2^0)$



➢ No sensitivity



Those limits are improved by ~10% if tau’s are included.

Scenario

light sleptons but heavy squarks

$M(\tilde{\chi}_2^0) \approx 3M(\tilde{q})$

Projectons wih 1fb^{-1}